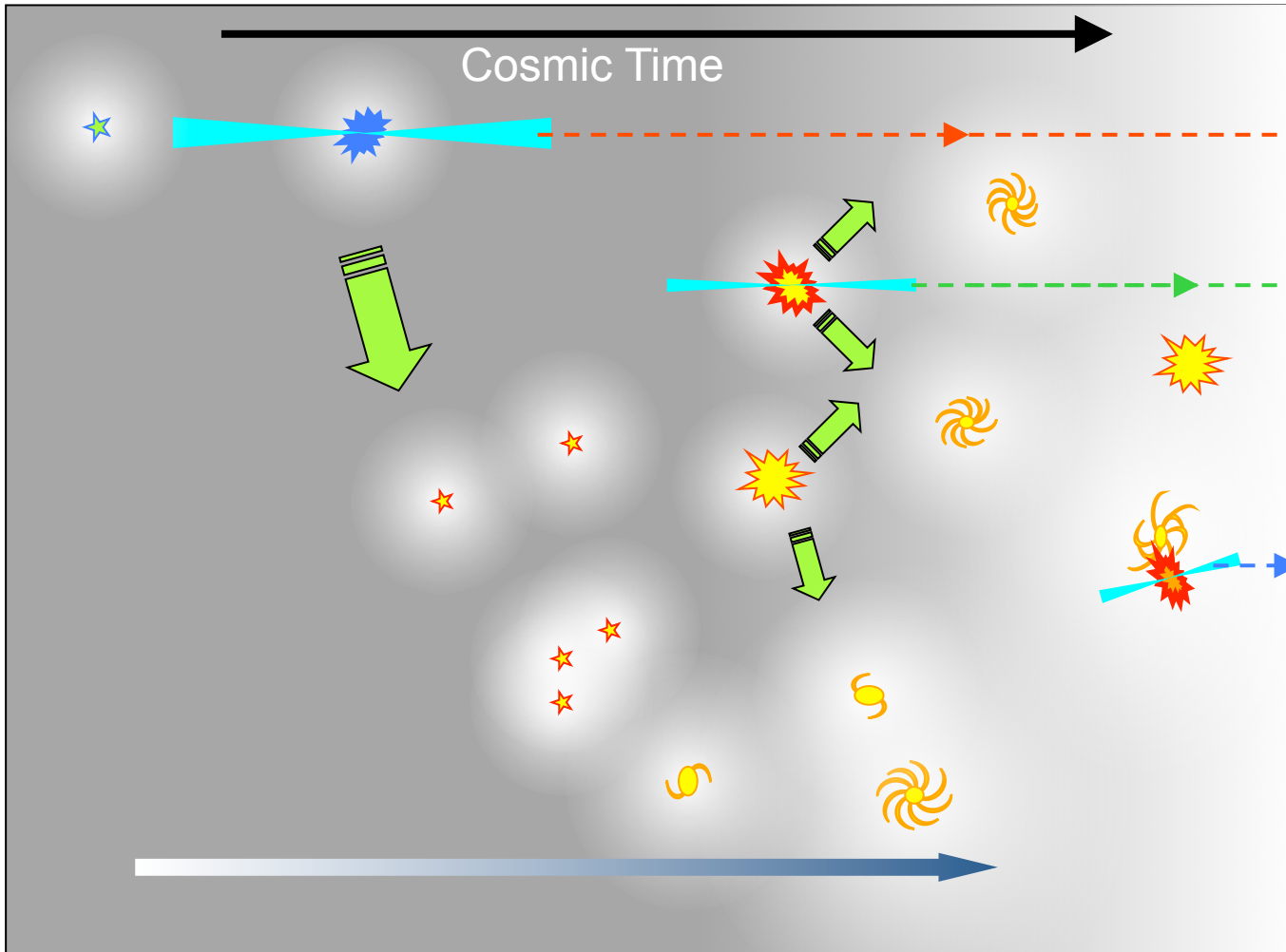
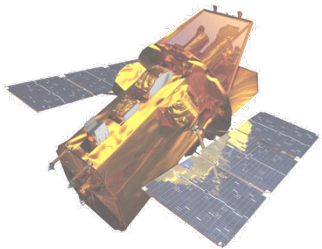


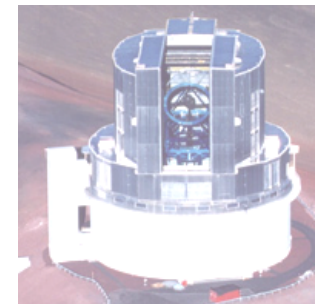
# GRBs as probes for the high-z Universe



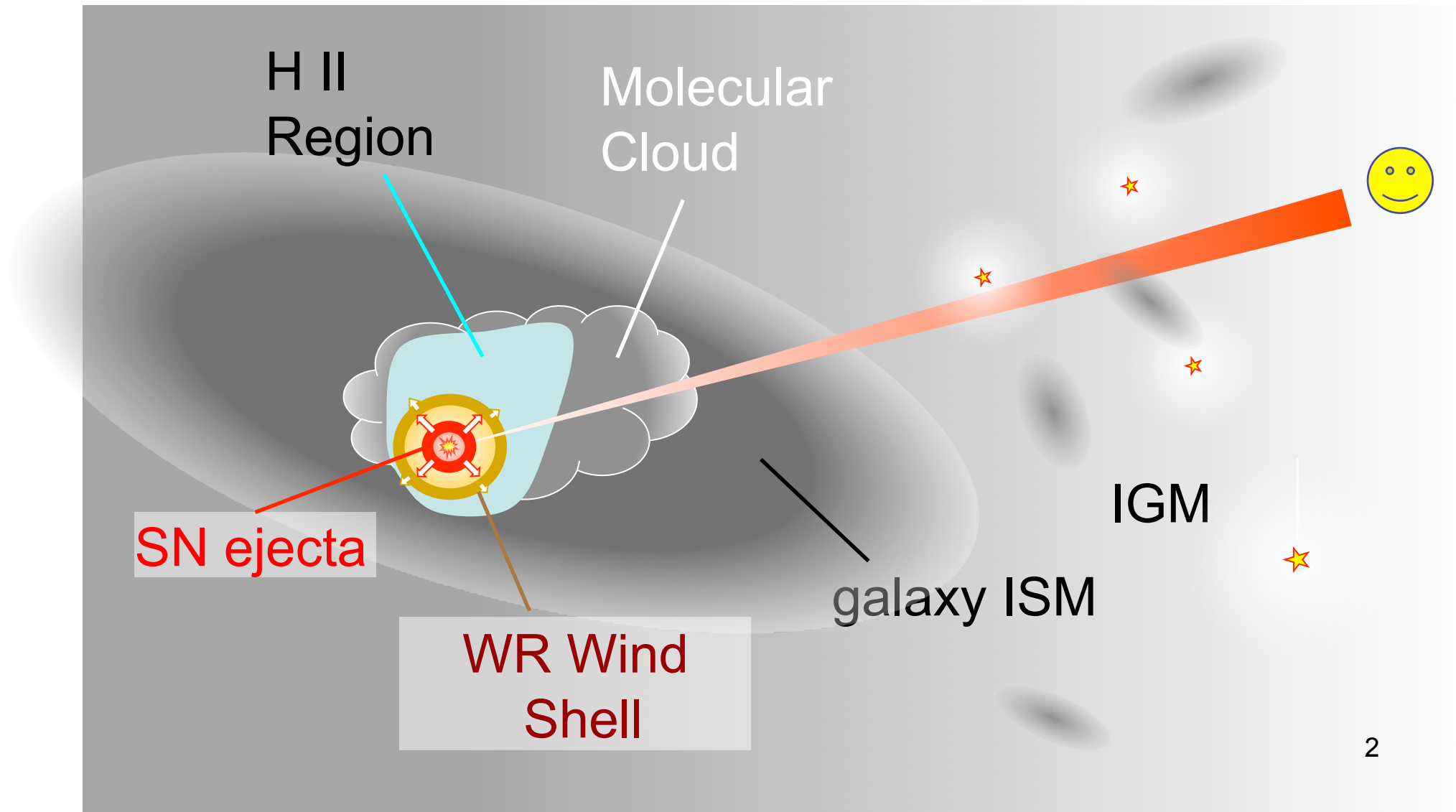
- GRB as a luminous light source
- GRB as a mark for a death of a massive star

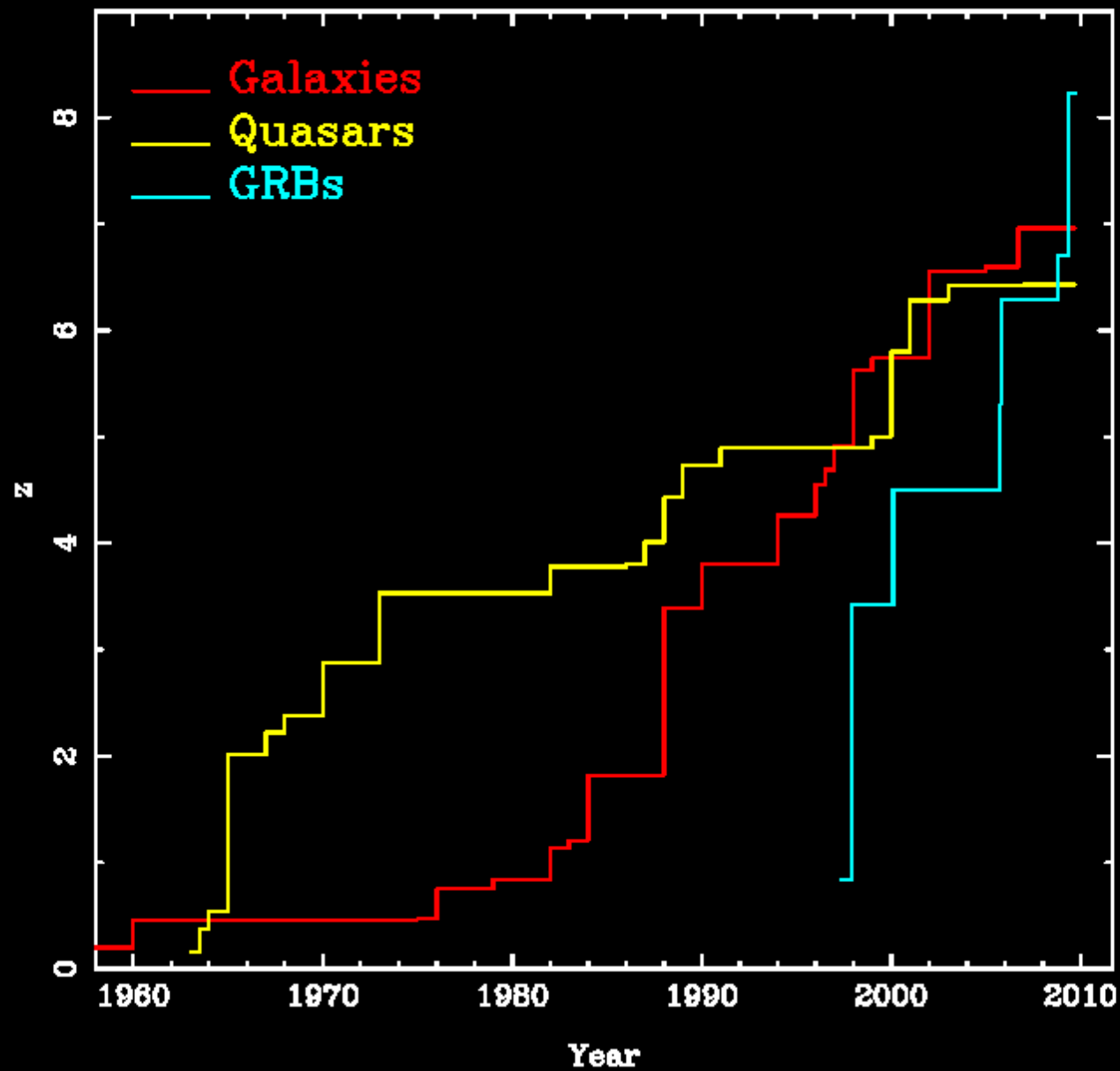


Nobuyuki Kawai (Tokyo Tech)



# GRB Environment





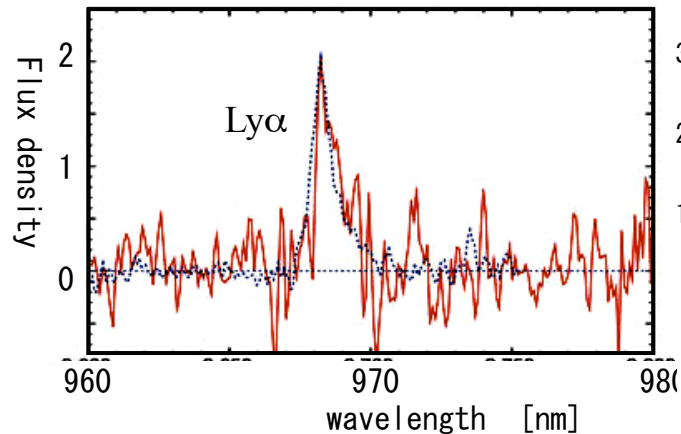
Age of universe  
= 630 Myr

Luminosity distance  
= 85 Gpc

Tanvir 2009

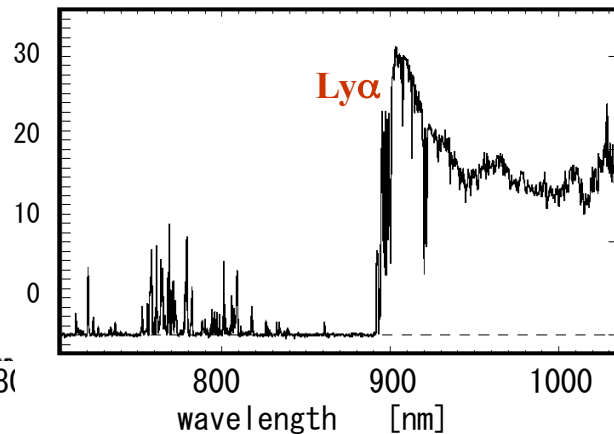
# optical/NIR spectra of highest- $z$ objects

**Galaxy**  
 **$z = 6.96$**



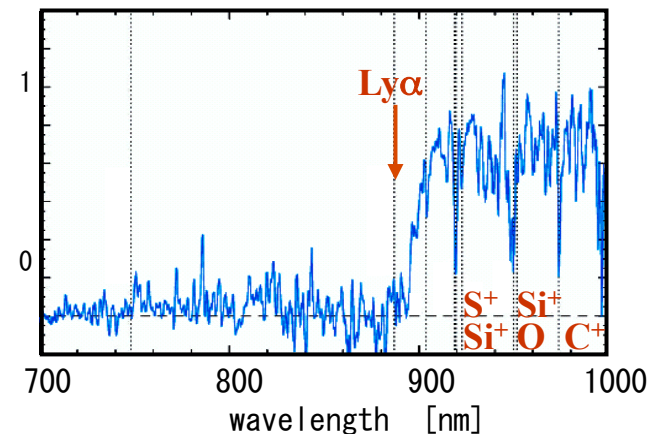
- Lyman alpha emitter
- can be found with systematic wide-field narrow band survey + spectroscopy
- little information in spectra (e.g. metal?)
- luminosity selected

**Quasar**  
 **$z = 6.4$**

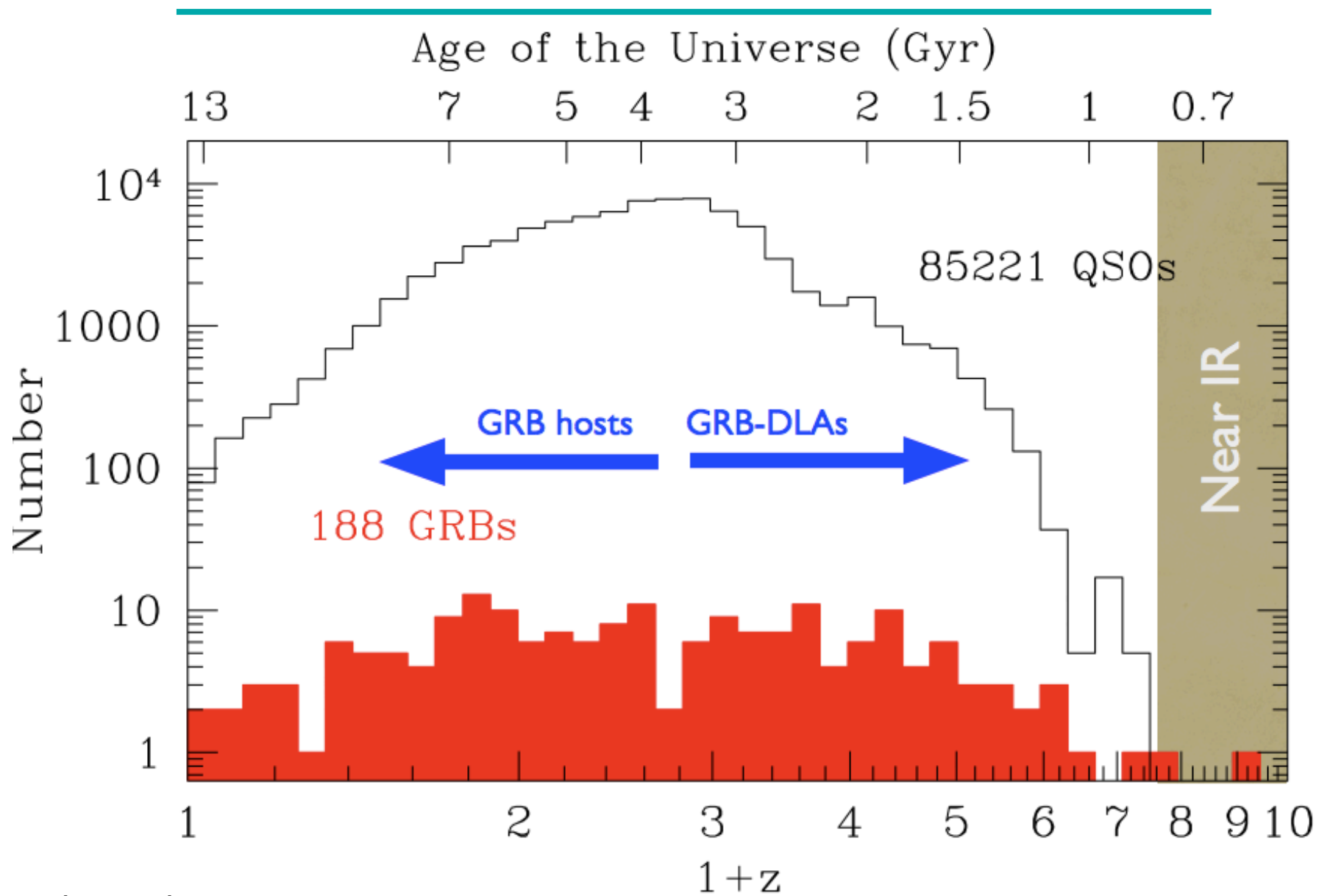


- very rare: only 10 at  $z > 6$  in SDSS
- steadily bright
- complicated spectra: difficult to interpret
- proximity effect
- luminosity-selected

**GRB**  
 **$z = 6.3$**



- rare:  $\sim < 5\%$  at  $z > 6$  ?
- bright at early phase
- simple intrinsic spectra: abundant information
- no proximity effect
- sampling normal star-forming galaxy



# GRBs probe ...

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- ◆ **Metallicity**

- ◆  $[S/H] = -1.3$  for GRB050904 at  $z=6.3$

- ◆  **$x_{\text{HI}}$ : IGM neutral hydrogen fraction**

- ◆ consistent with 0.0 at  $z=6.3$  ( $<0.6$  at  $3\sigma$ )

- ◆ **SFR as a function of  $z$**

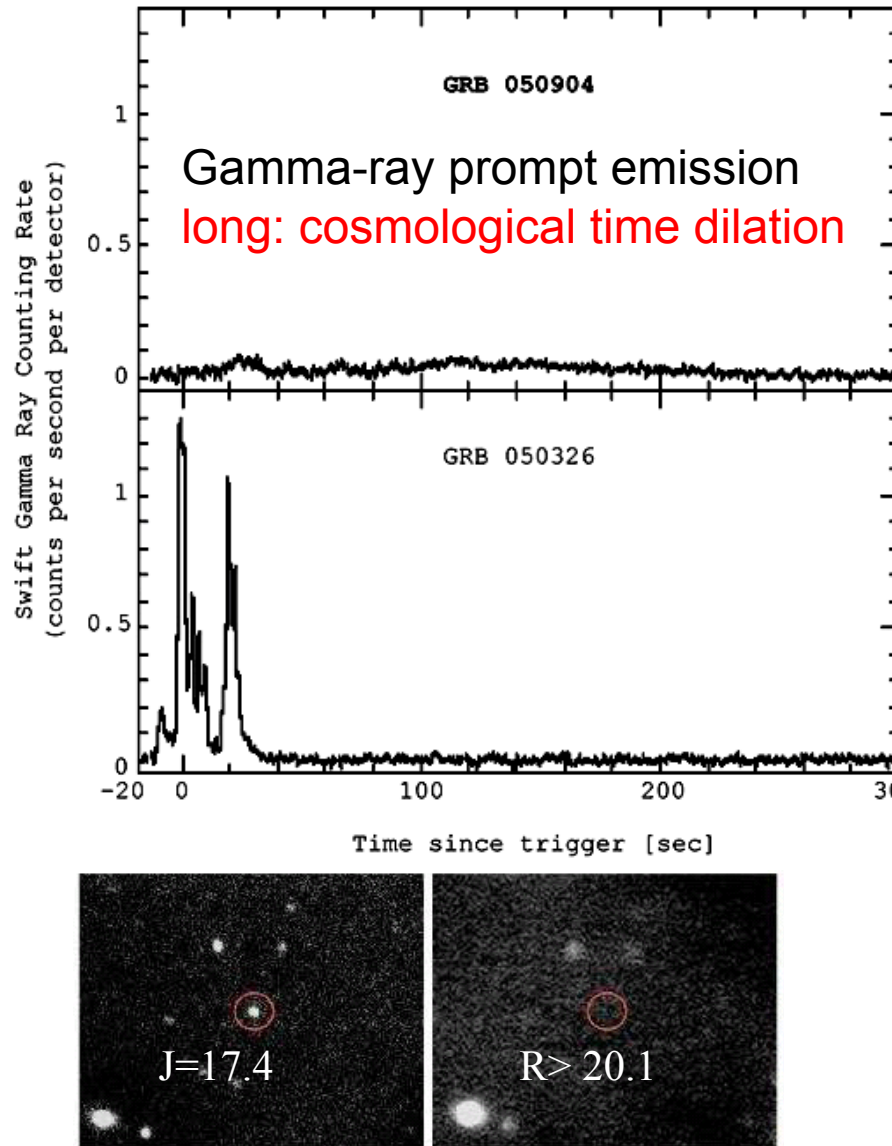
- ◆ statistics of GRBs with **known redshifts**

- ◆ **Nature of the pop-III stars**

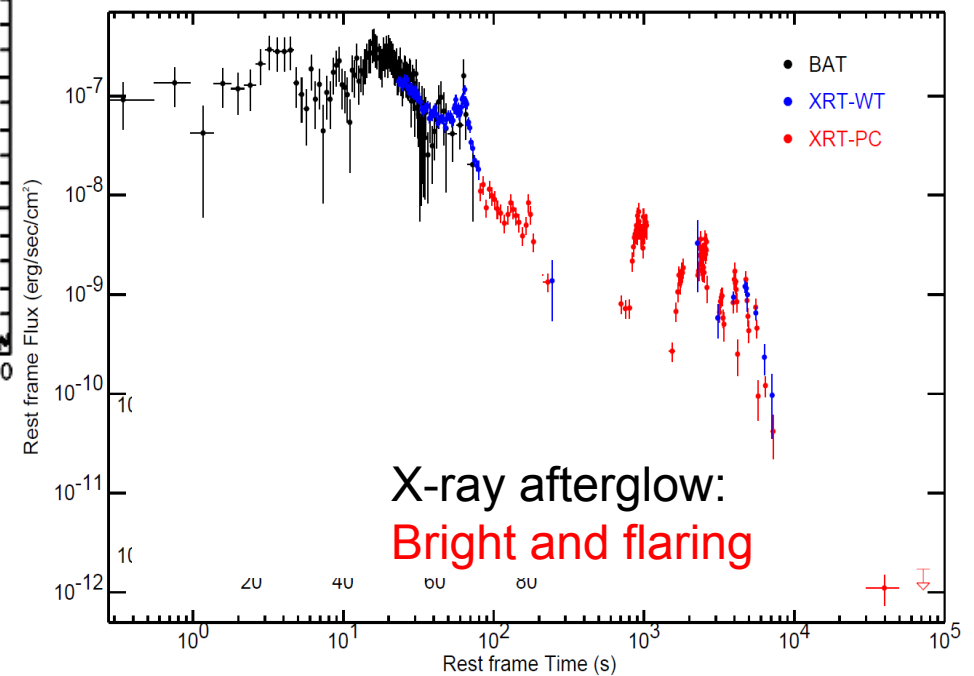
- ◆ how do they explode?
- ◆ SN products (Fe,  $\alpha$ -elements) similar to low- $z$  thermonuclear/core-collapse SNe?

# GRB 050904

Cusumano et al. 2006



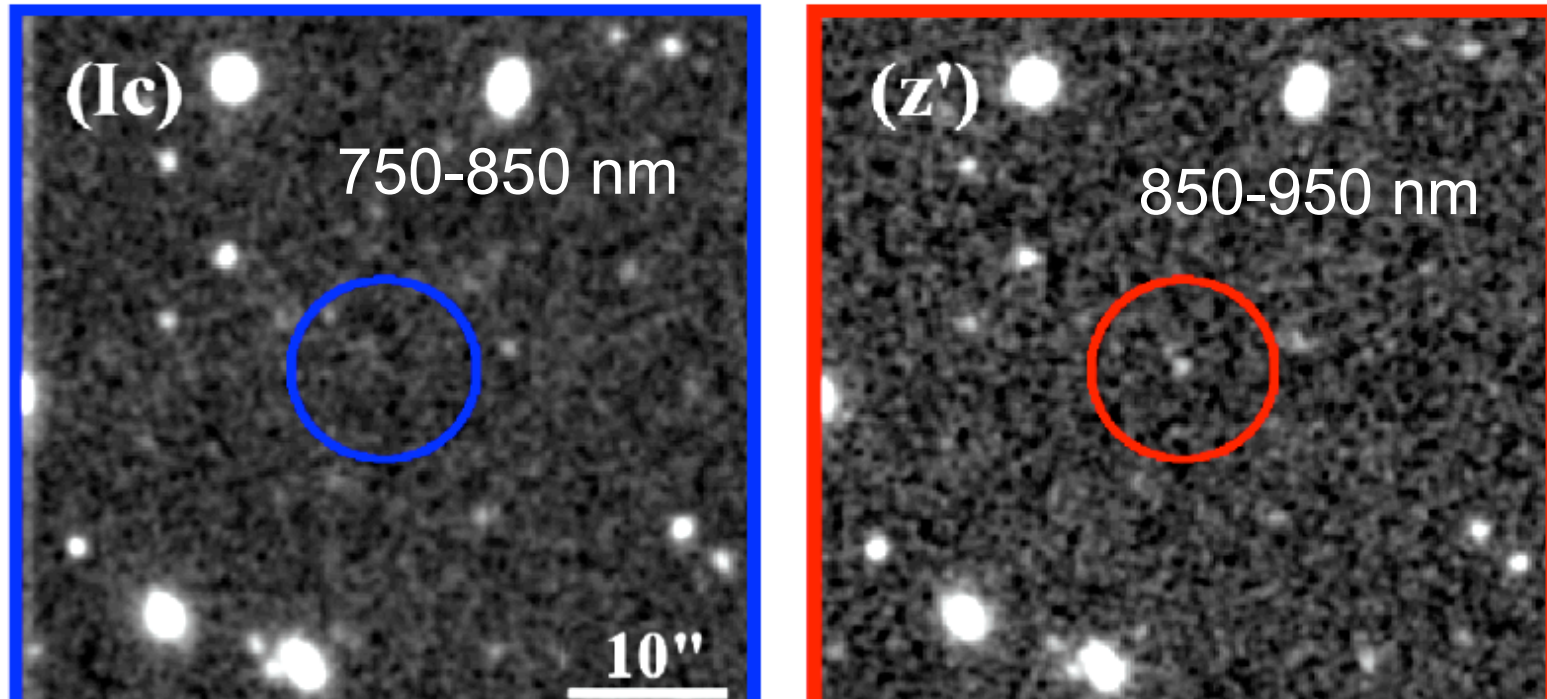
Long GRB (duration  $T_{90} = 225$  s)  
detected by *Swift* on 4 September  
2005, 01:51:44 UT,



Bright in infrared, but dark in the optical band

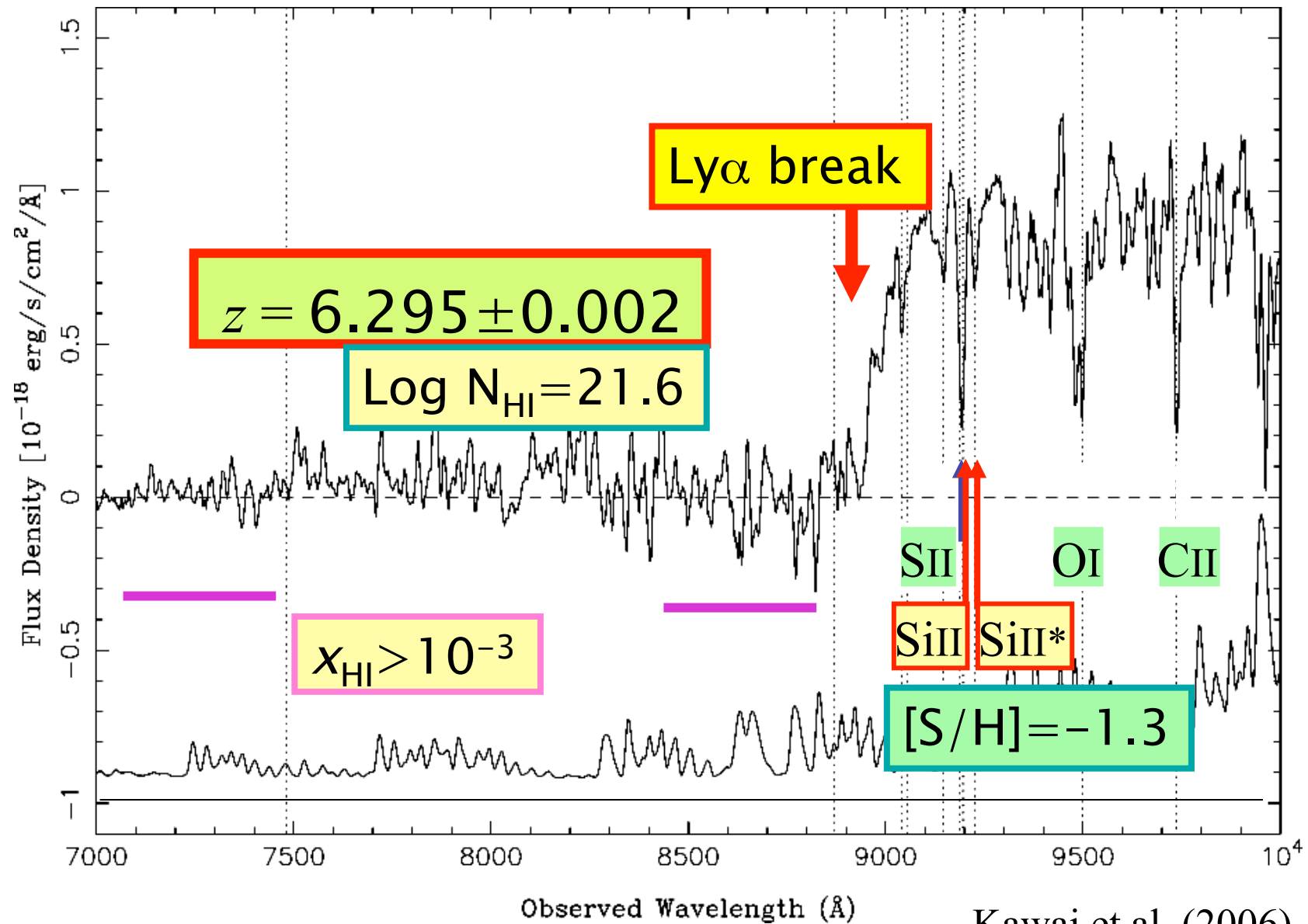
Haislip et al. 2006

# Subaru Images ( $t_0 + 3$ days)



- ◆  $z'(AB) = 23.71 \pm 0.14$  mag,
- ◆ No detection in Ic band.
- ◆  $\rightarrow$  Ly break at 8500–9000 Å .

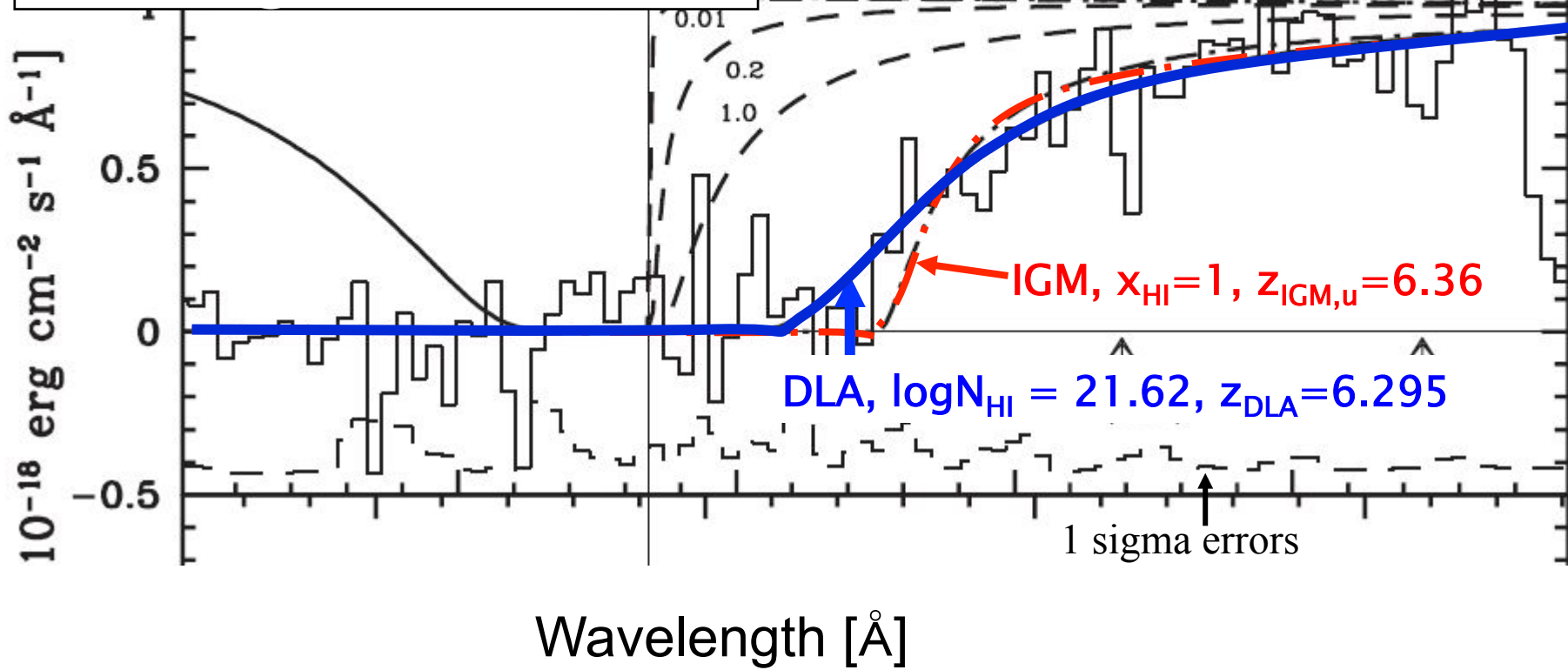
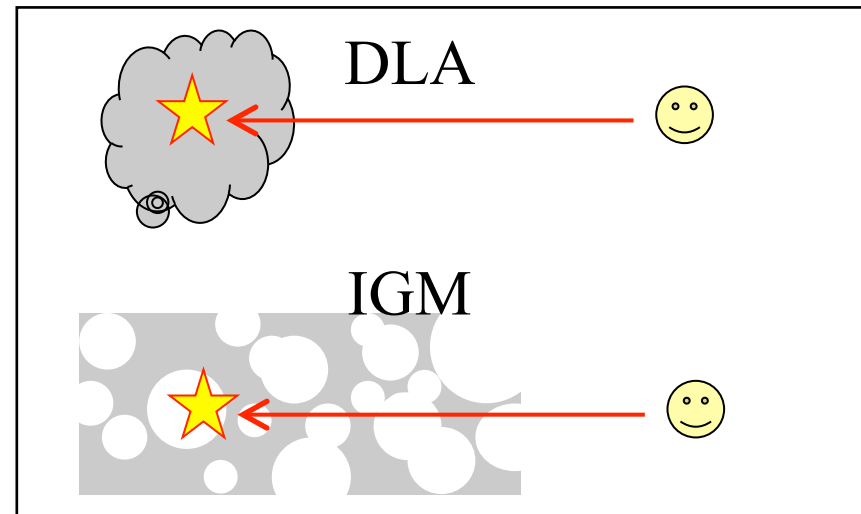
# GRB 050904 at t=3.4 d



Subaru FOCAS 4.0 hrs,  $\lambda/\Delta\lambda \approx 1000$

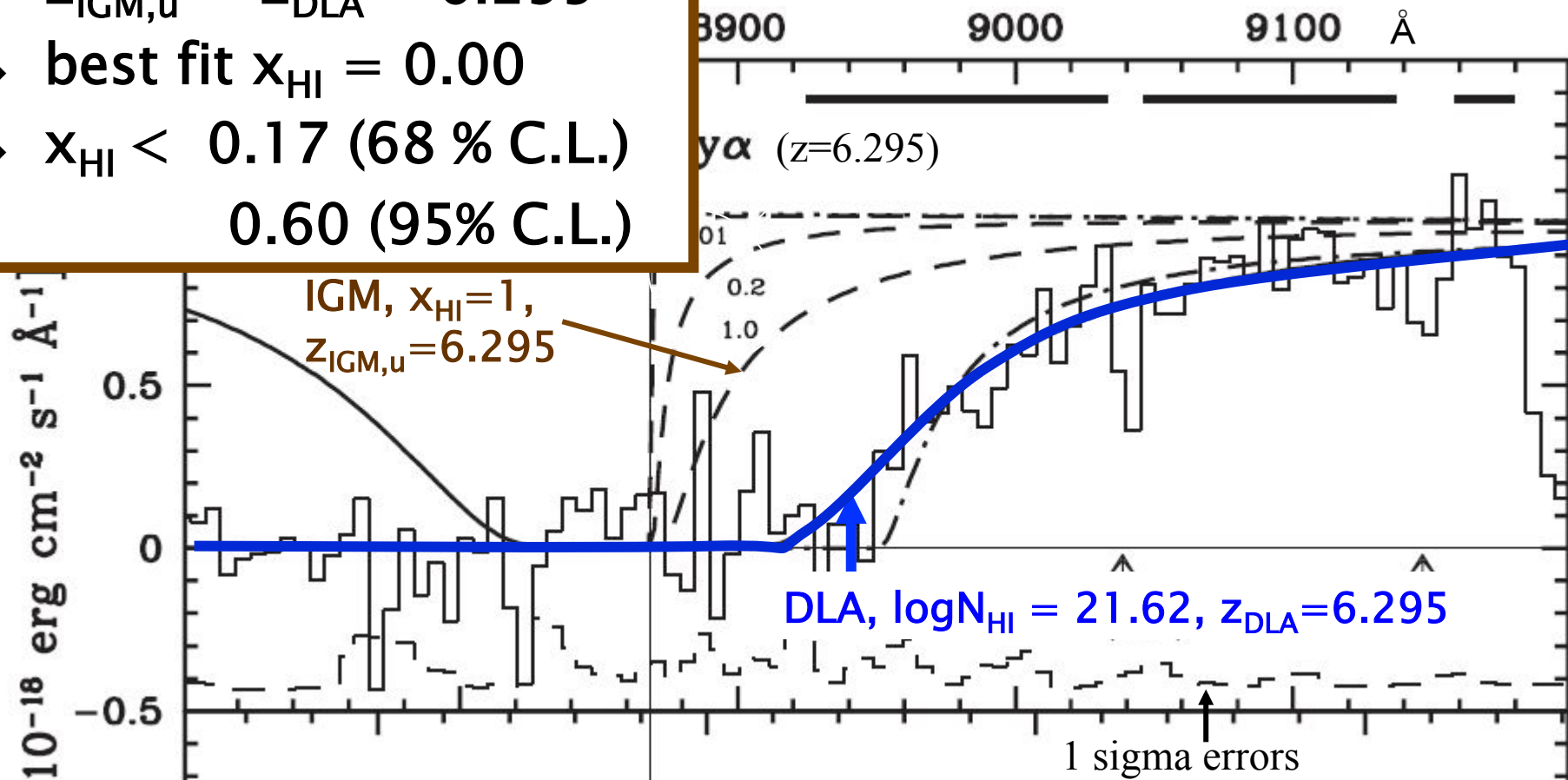
Kawai et al. (2006) <sup>9</sup>  
Totani et al. (2006)

# Damping Wing



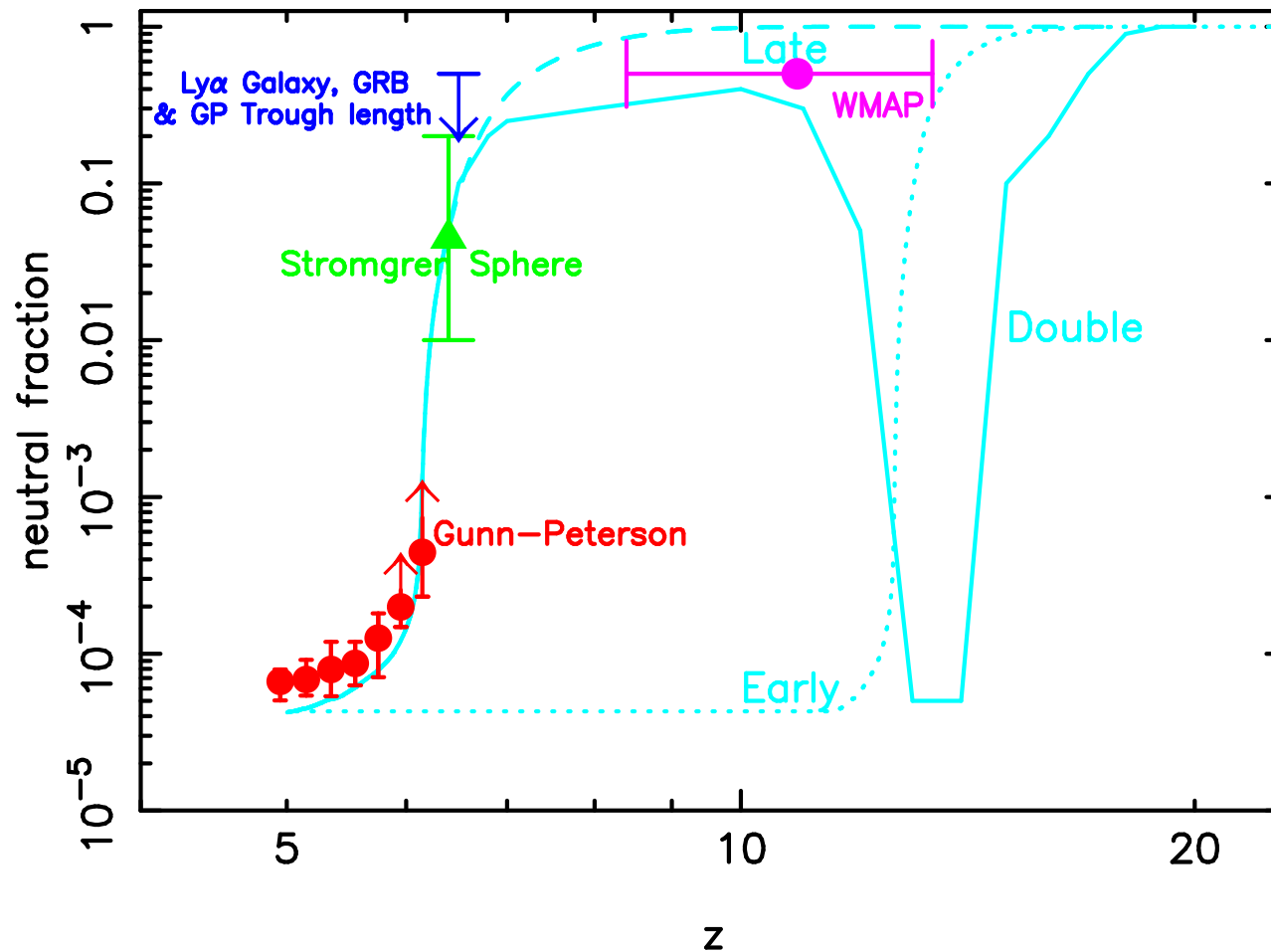
# Constraint on $x_{\text{HI}}$ ?

- ◆  $z_{\text{IGM,u}} = z_{\text{DLA}} = 6.295$
- ◆ best fit  $x_{\text{HI}} = 0.00$
- ◆  $x_{\text{HI}} < 0.17$  (68 % C.L.)  
0.60 (95% C.L.)



Neutral IGM is not dominant in the damping wing,  
but it does affect the wing shape if  $x_{\text{HI}} \sim 1$

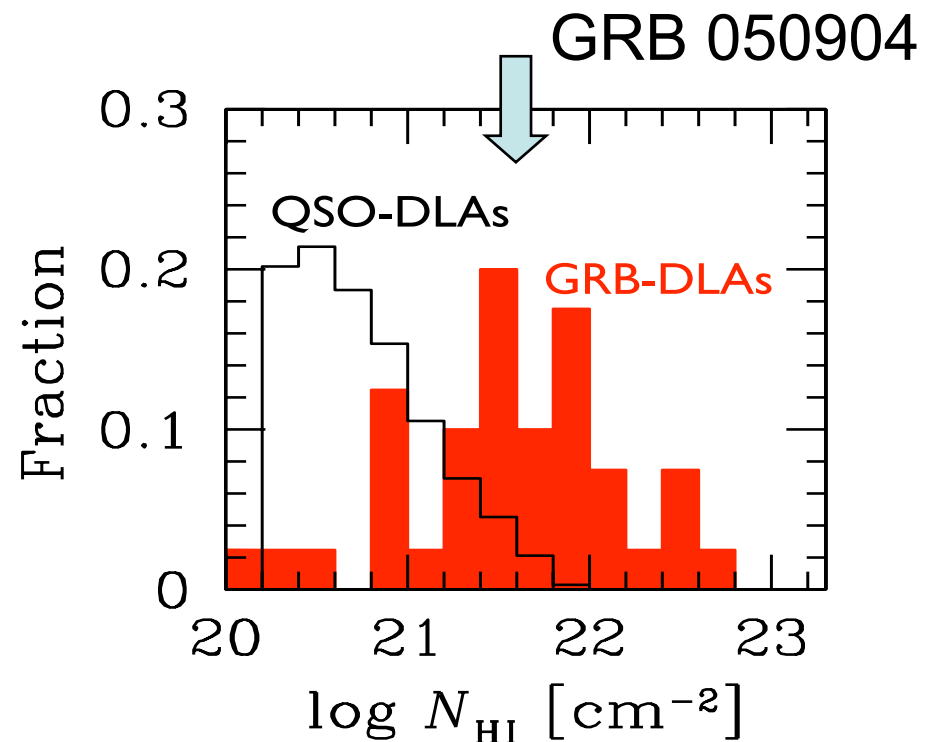
# Comparison with other measurements of reionization



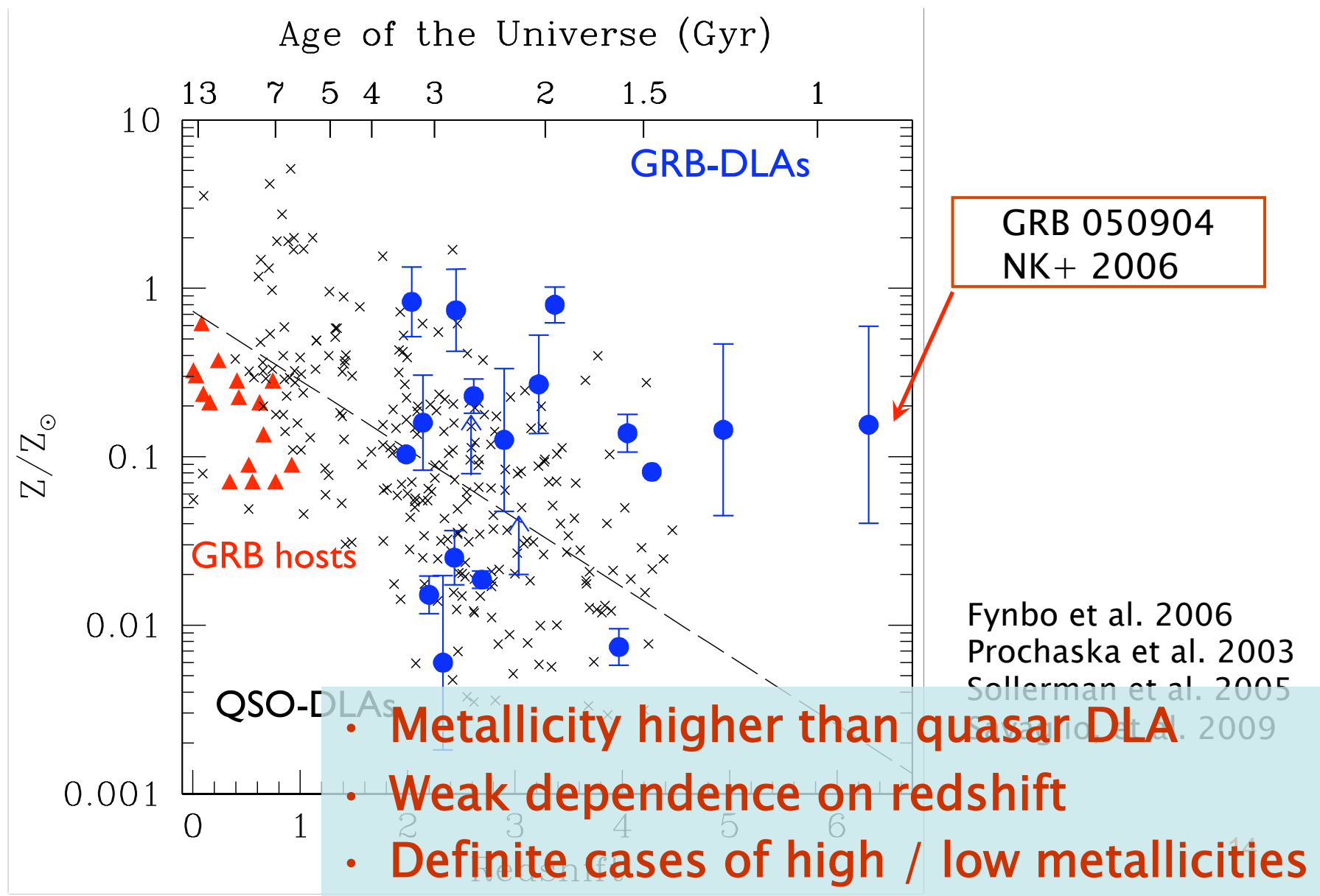
# Prospects for constraining $x_{\text{HI}}$ with GRBs

- **low  $N_{\text{HI}}$  GRBs?**

- only weak constraint on  $x_{\text{HI}}$  due to DLA with  $\log N_{\text{HI}} > 21.5$
- However, there are GRBs ( $\sim 20\%$ ) with  $\log N_{\text{HI}} \leq 20$
- promising chance for a better constraint on  $x_{\text{HI}}$  by IGM damping wing

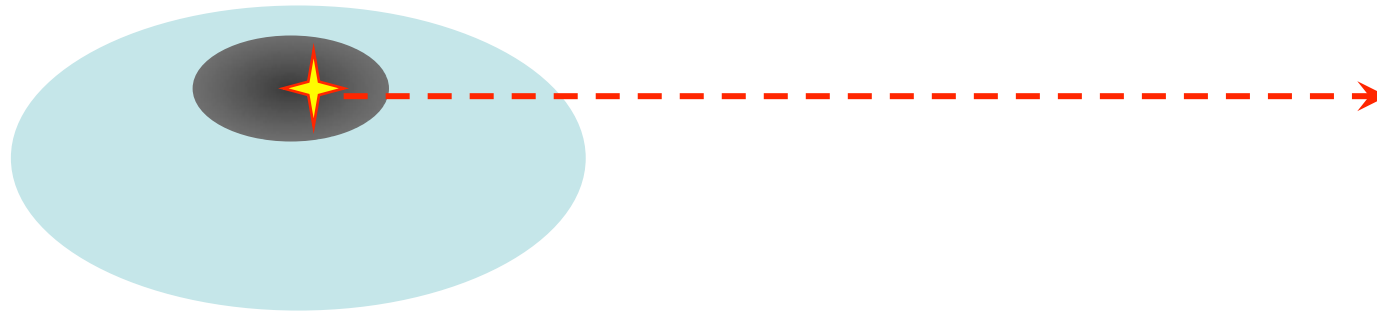


# Cosmic Chemical Evolution

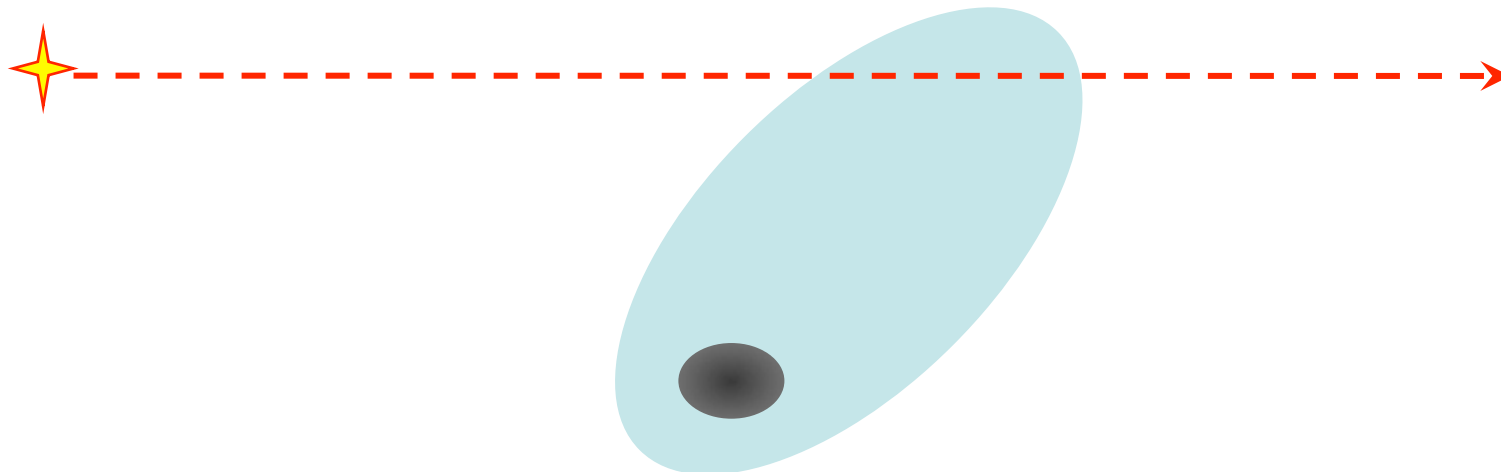


# DLA in GRB and Quasar

GRB



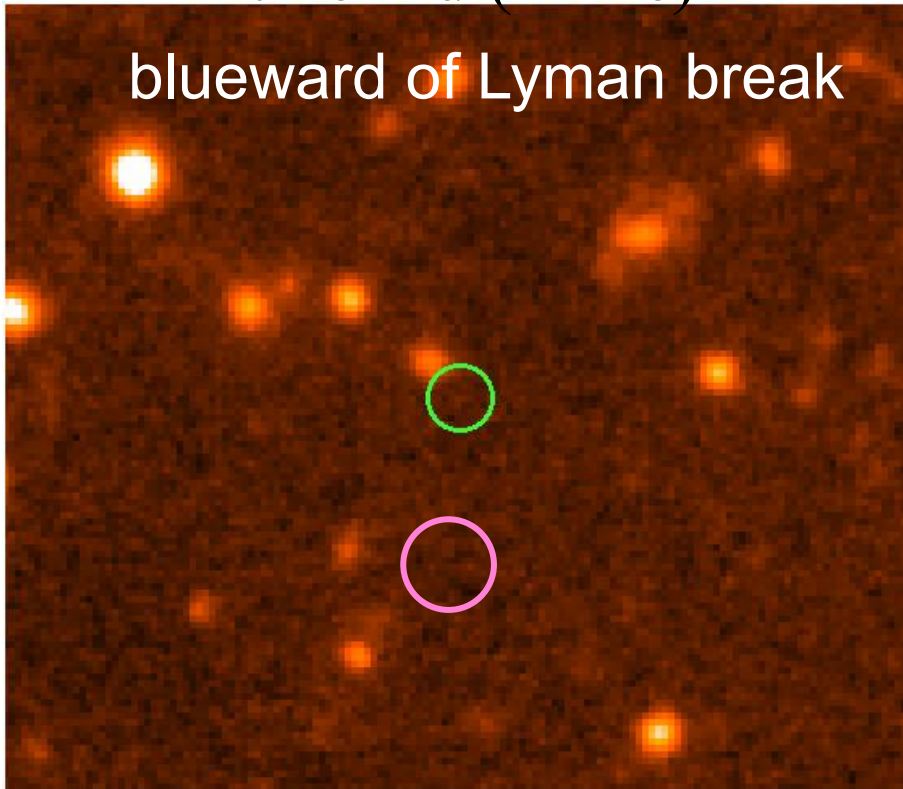
Quasar



# GRB 050904 Host galaxy

$i'$ -band (24 ks)

blueward of Lyman break

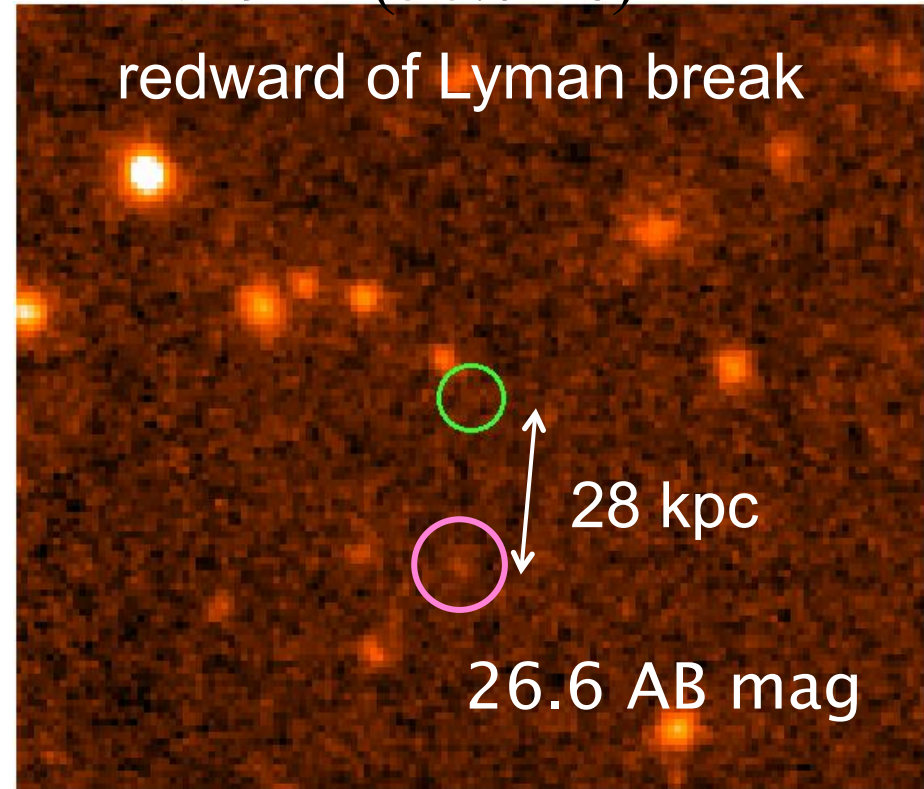


Dec 27 '05--Jan 01 '06  
( $t_0+115\sim119$ d)

Aoki et al. 2006

NB921 (56.7 ks)

redward of Lyman break

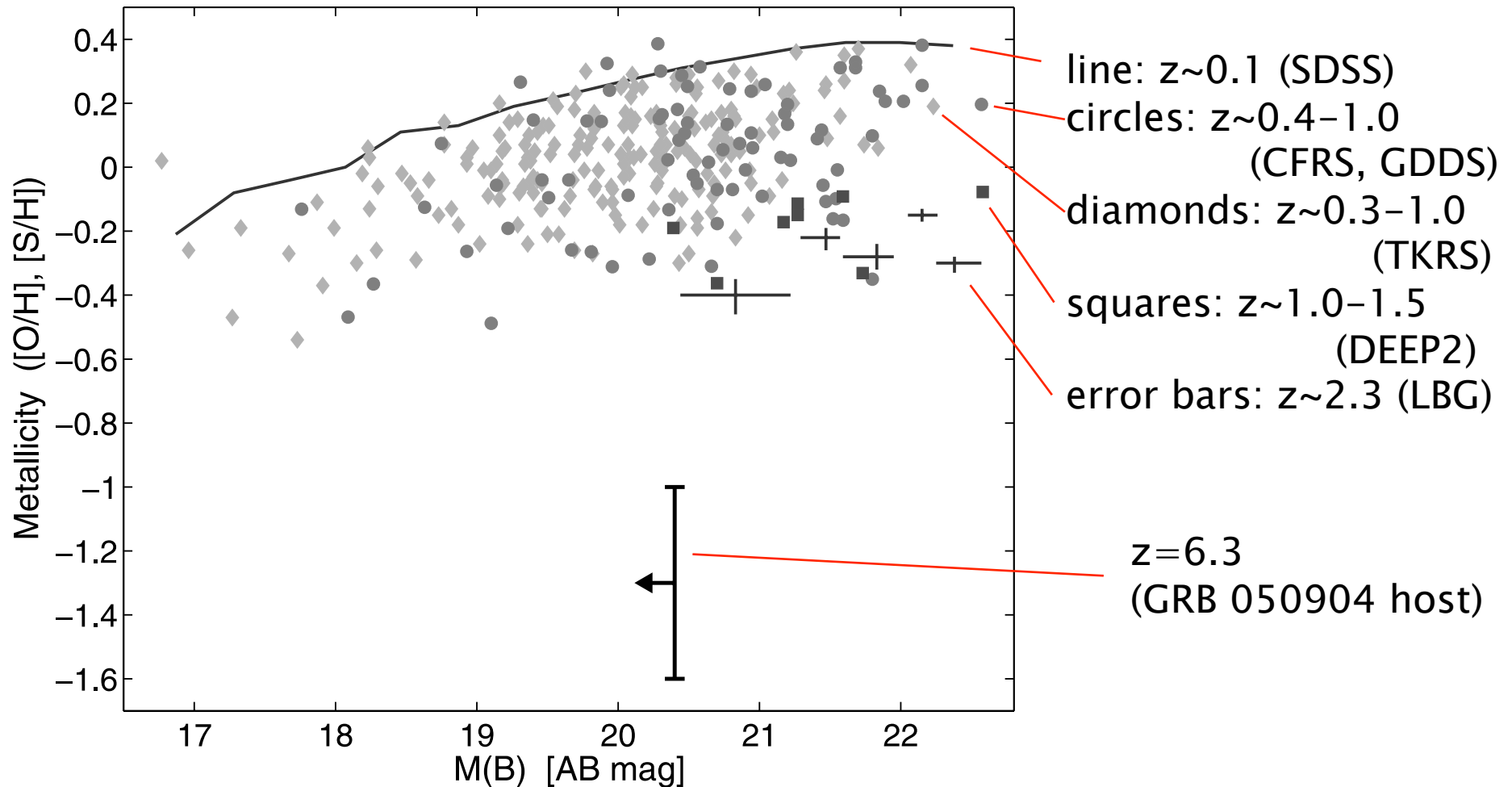


$> 26.4$  AB mag ( $3\sigma$ )

$M_{1260} > -20.4$  mag  $\rightarrow L < L_*$

SFR  $< 7.5 M_{\text{sun}}/\text{yr}$

# GRB 050904 Host galaxy

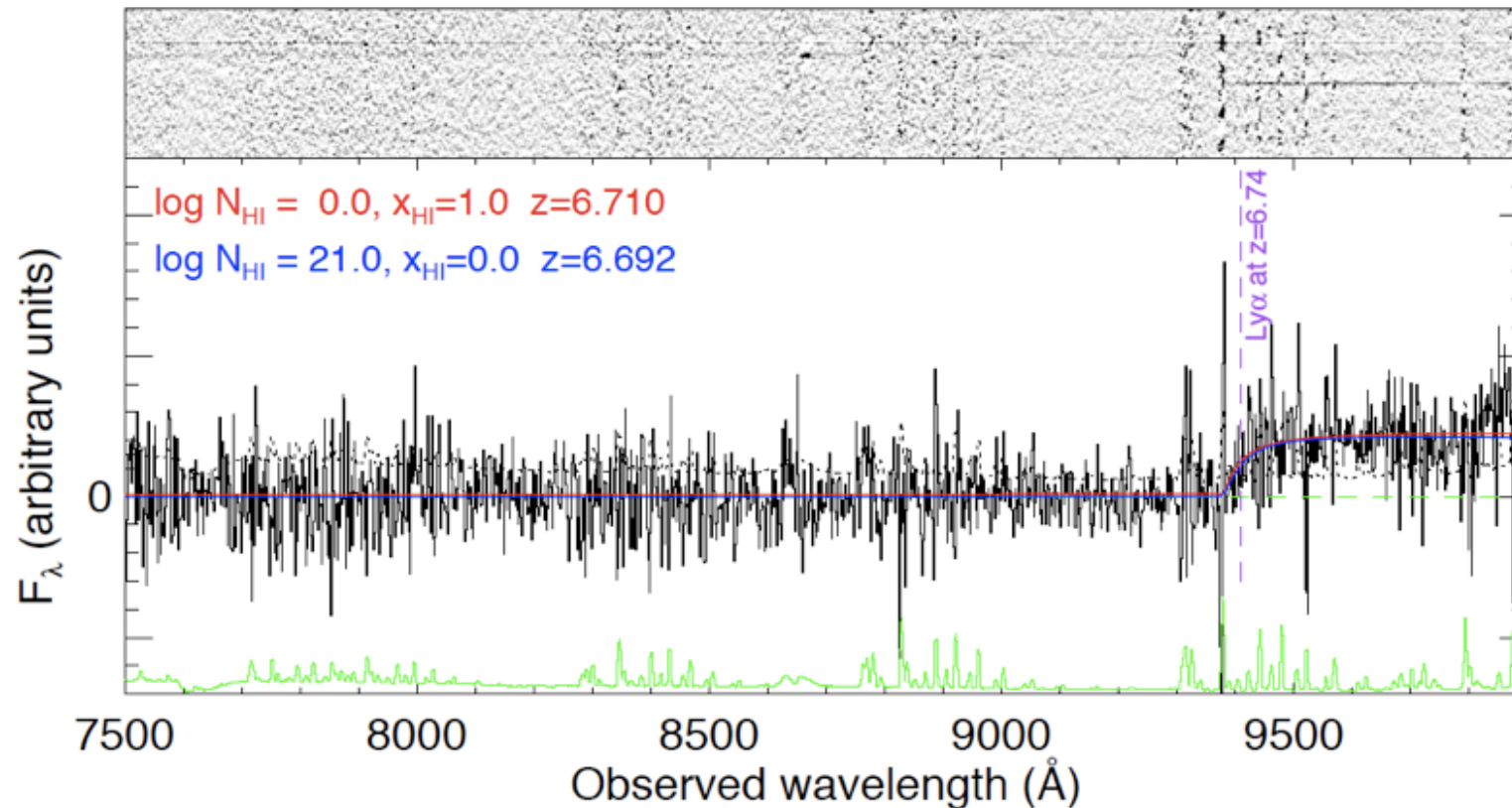


Berger et al. 2007

$$M_{2200} > -20.3 \text{ mag} \rightarrow L \leq L_*$$

$$\text{SFR} < 5.7 M_{\text{sun}}/\text{yr}$$

# GRB 080913 @ $z \sim 6.7$



(Greiner+'09)

2-3 hrs,  $z' \sim 24.5$ (AB), 2400 s exp.

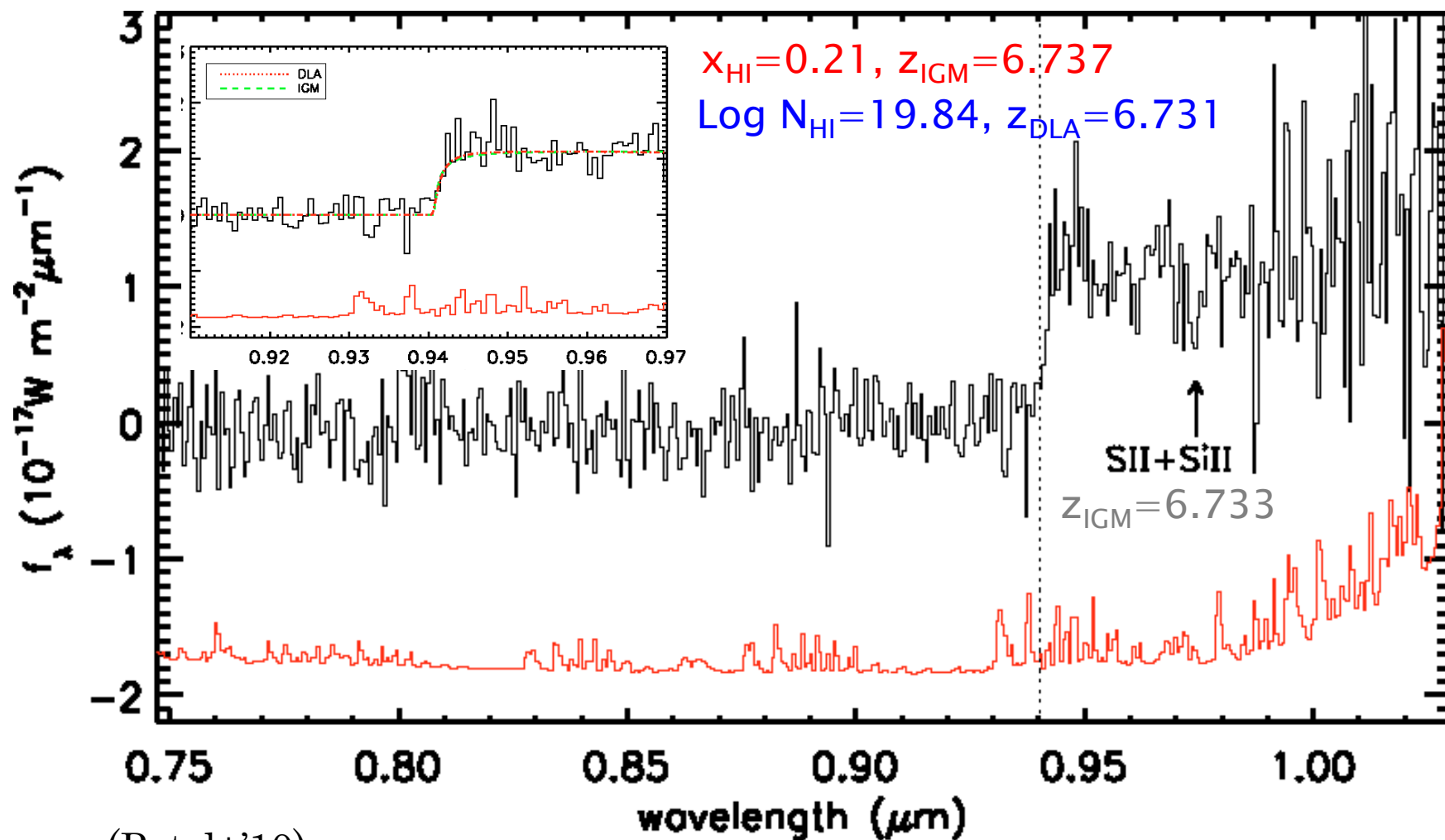
damping wing detected, but difficult to discriminate DLA or IGM

c.f. GRB 050904,  $z \sim 6.3$

3.4 days,  $z' = 23.7$ (AB),

4 hr exp.

# GRB 080913 (reanalysis)



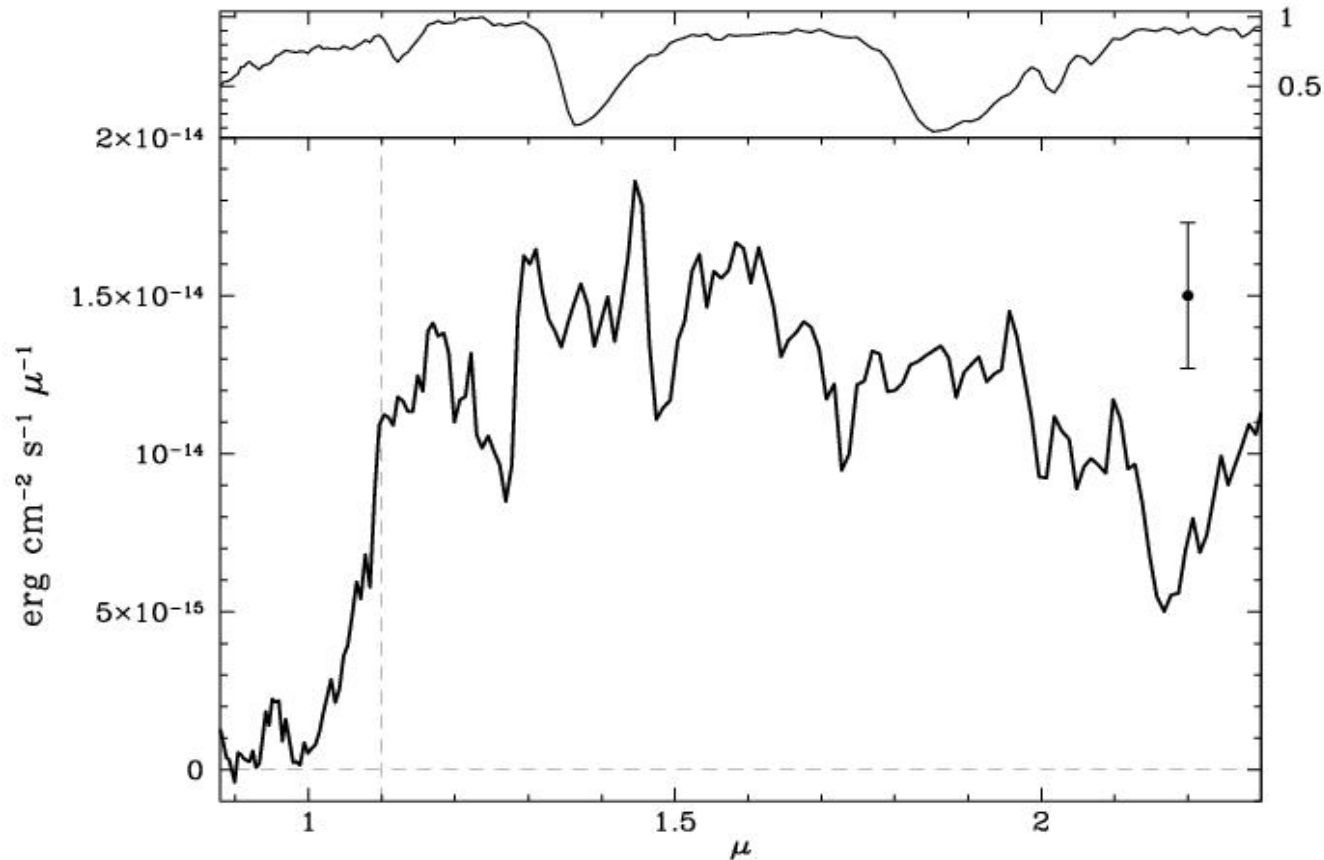
(Patel+'10)

additional 3.5 hour exp at +3 days: S/N improved x1.3

$x_{\text{HI}} < 0.73$  (90%) (IGM+DLA model)

# GRB 090423 @ $z \sim 8.1$

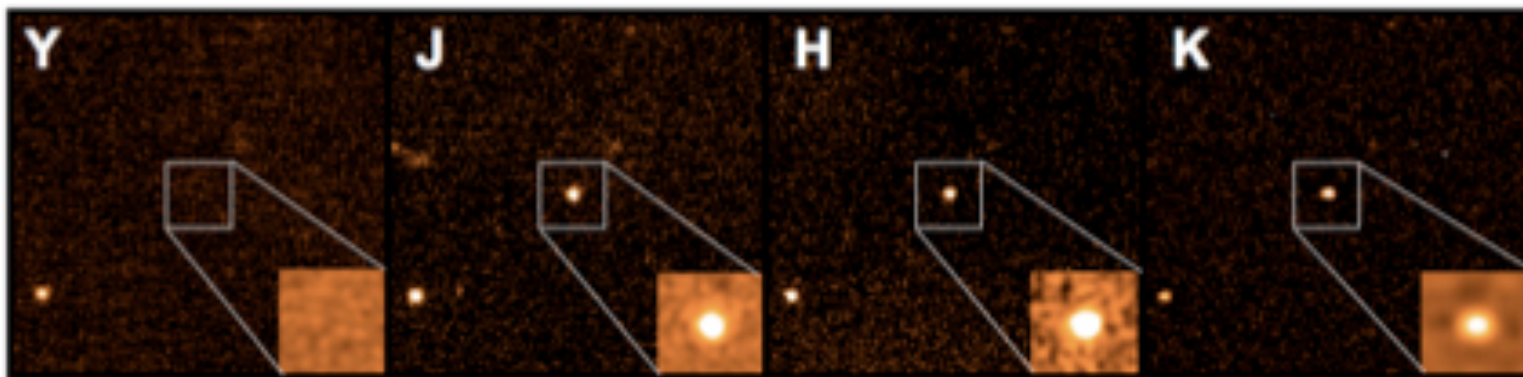
spectrum taken with the Amici prism on the TNG/NICS camera at  $\sim 14$  hrs



$$z = 8.1^{-0.3}_{+0.1}$$

Salvaterra+'09 TNG/NICS,  
R $\sim 50$   $\sim 14$  hrs

# GRB 090423

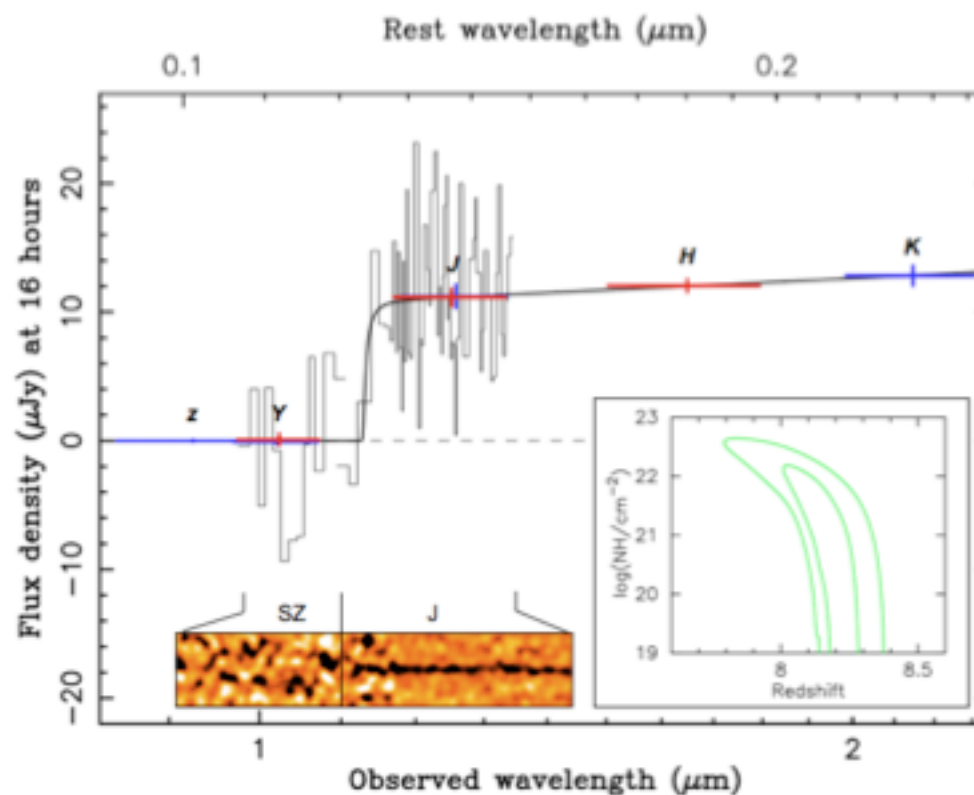


Tanvir+'09

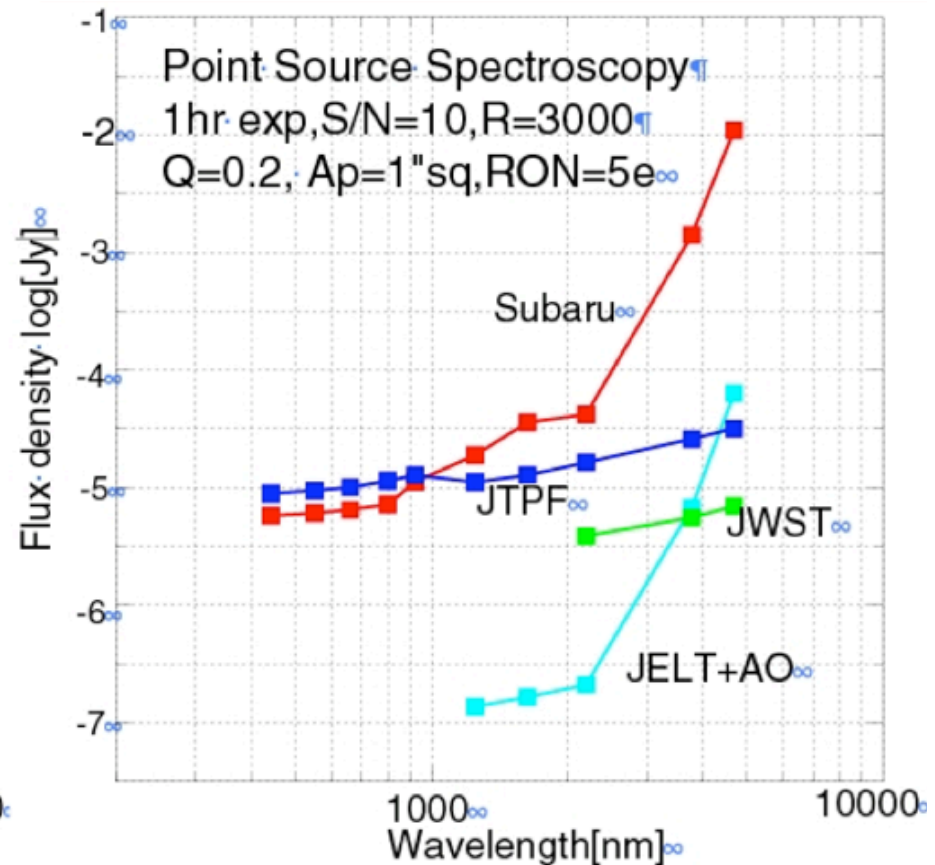
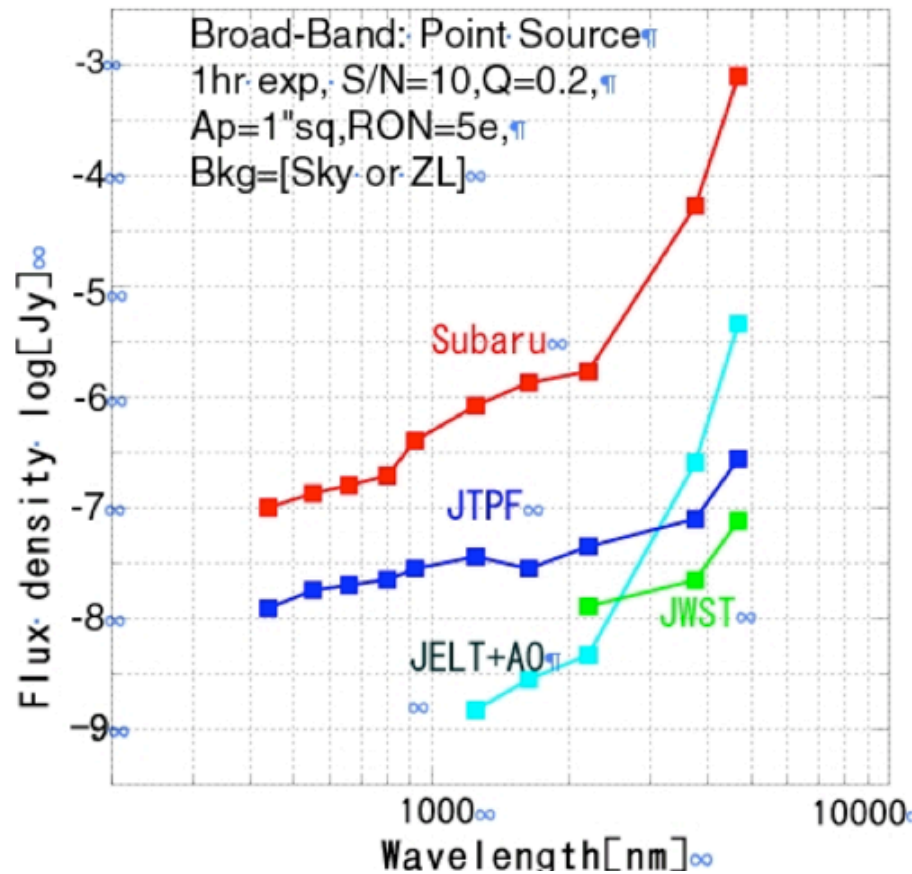
VLT/ISAAC, ~17.5hr,

J~20.8 ~30 min exp.

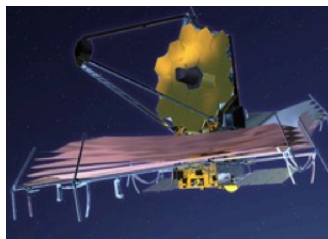
Only upper bound on  $N_{\text{HI}}$   
(=no detection of damping wing)



# 30m/JWST sensitivity vs. GRBs

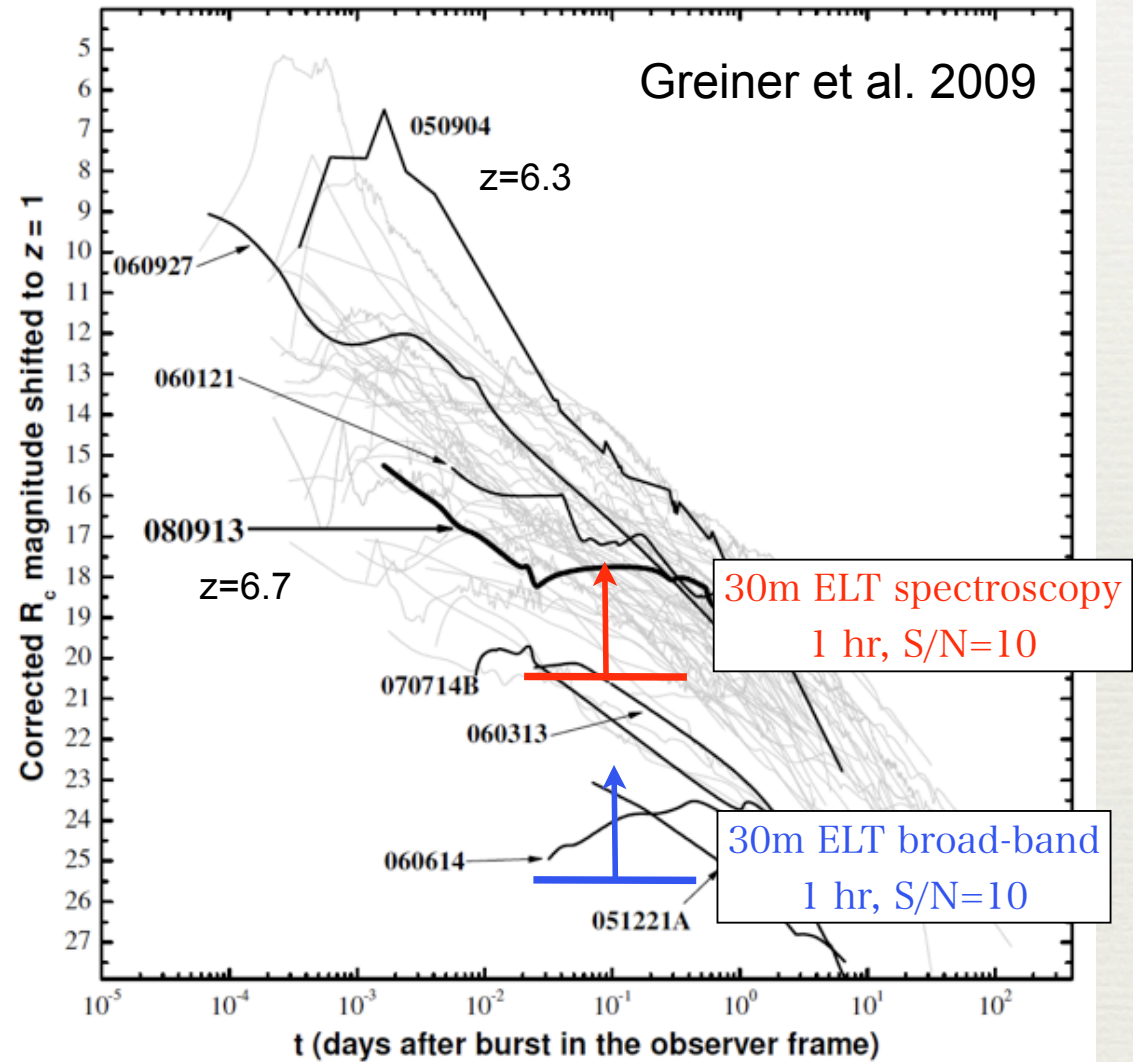
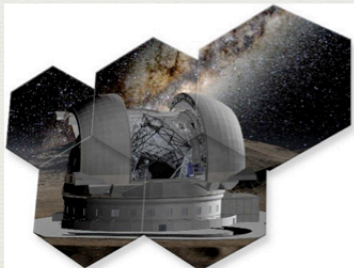
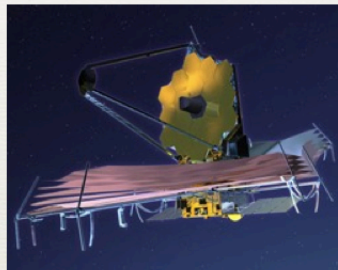


M. Iye



# 30m/JWST sensitivity vs. GRBs

- ♦ convert into R mag,  $z=1$ 
  - ♦  $F_\nu \propto t^{-1} \nu^{-1}$
- ♦ observe at 1 day after  $z=10$  burst  $\rightarrow \sim 0.1$  day for  $z=1$



# # of GRBs required for measuring reionization

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Totani 09

- ◆ ~1% of GRBs at  $z > 10$
- ◆ ~20% of GRBs have  $\log N_{\text{HI}}/\text{cm}^{-2} < 20$
- ◆  $\rightarrow$  0.2% of GRBs can be used to measure  $x_{\text{HI}}$  at  $z \sim 10$
- ◆ 500 GRBs required! We need to be patient...
- ◆ further reducing factors:
  - ◆ NIR follow-up availability
  - ◆ dark GRBs (hopefully not important at very high- $z$ )
  - ◆ gamma-ray sensitivity (Swift level or better)
  - ◆ afterglow brightness (ELT/JWST will be OK)
- ◆ high sensitivity, high event-rate GRB mission desirable in the ELT/JWST era!

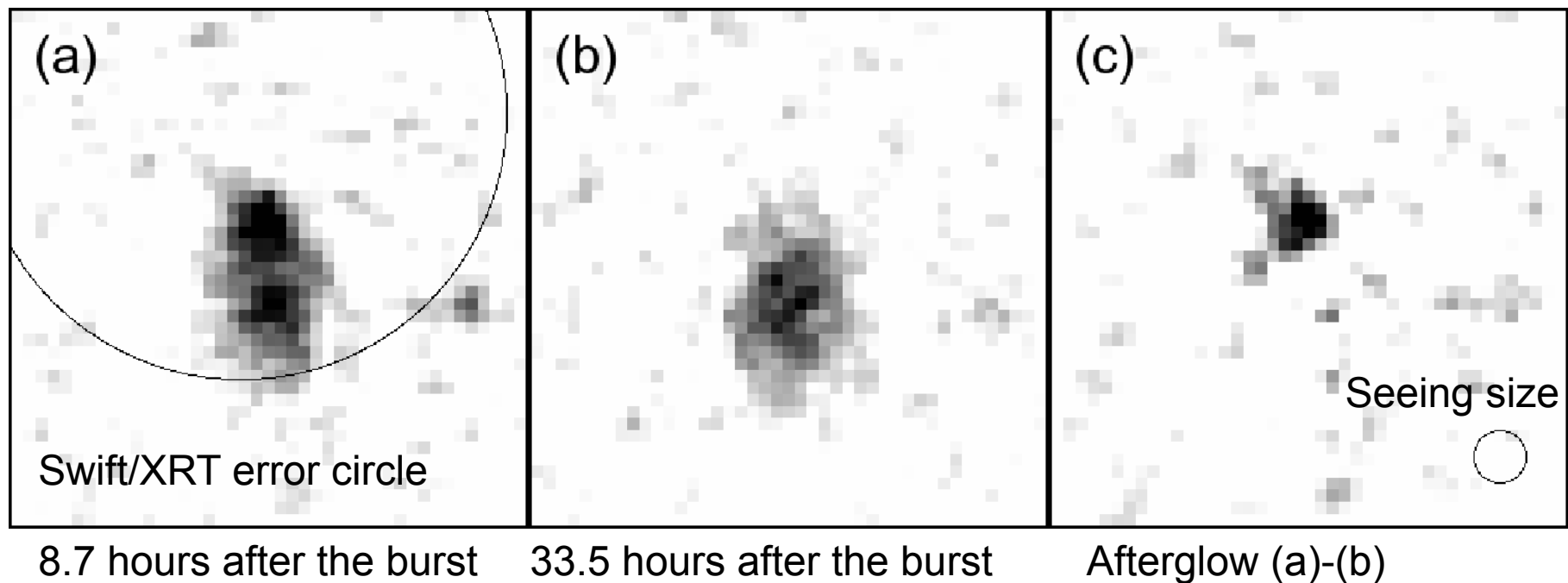
# GRB 080325: A dark GRB in a metal-rich host?

No optical detection of the afterglow within Swift/XRT error circle

Subaru/MOIRCS J, Ks band ToO obs.

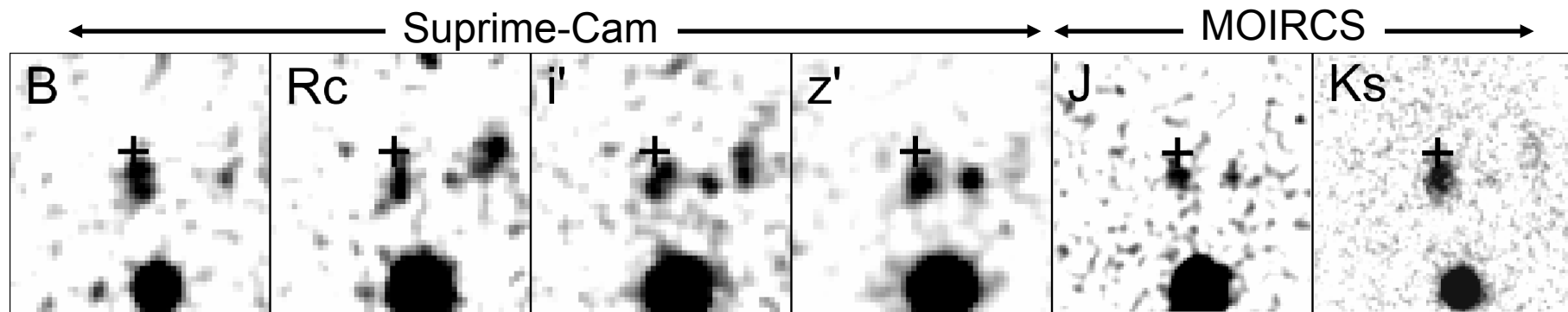
→ Detection in Ks band (Ks=22.8)

MOIRCS Ks band (5".0 x 5".0)



# GRB 080325 host: imaging at +1 year

Hashimoto et al. 2010



10'' x 10''

SFH = constant SFR

$\tau = 10\text{Myr}, 100\text{Myr}, 1\text{Gyr}, 10\text{Gyr}$   
instantaneous burst

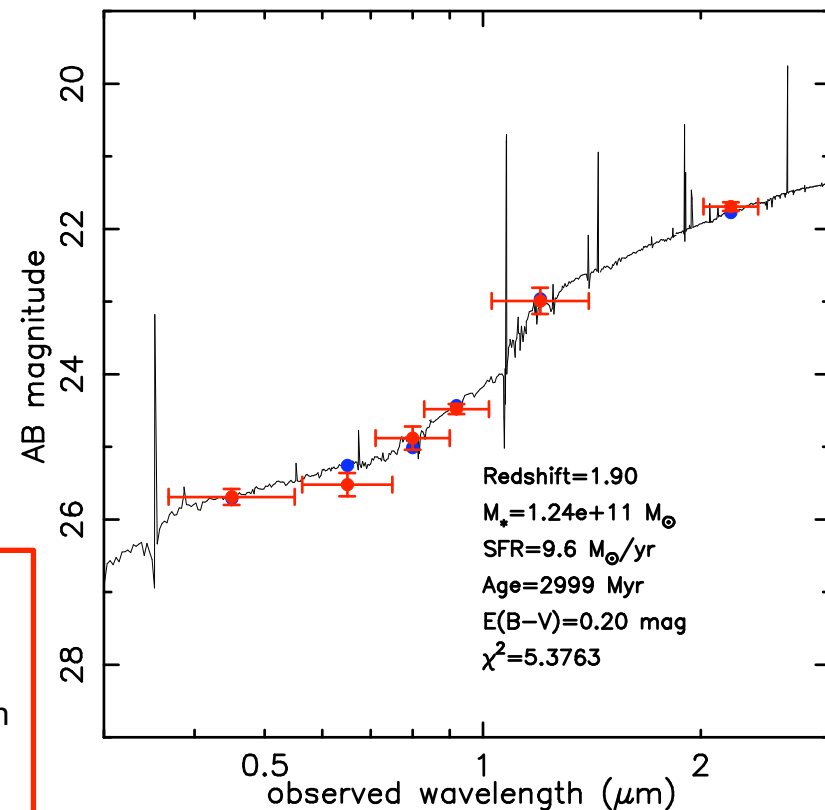
IMF = Salpeter

Stellar population synthesis model  
= PEGASE.2

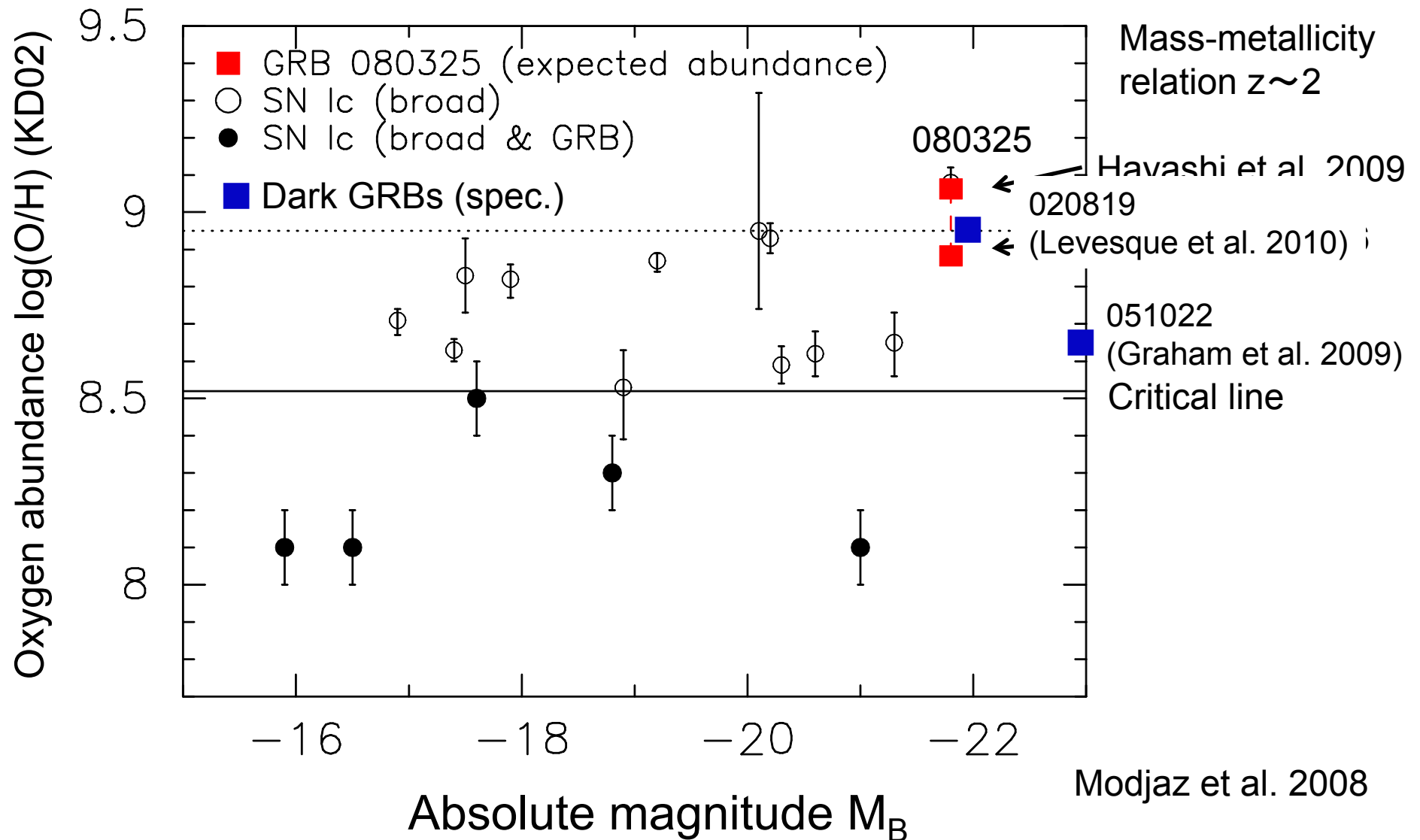
$$\text{Redshift} = 1.9^{+0.3}_{-0.15} \quad \text{SFR} = 9.6^{+41}_{-5} M_{\text{sun}}/\text{yr}$$

$$A_{V,\text{host}} = 0.8^{+0.6}_{-0.2} \text{ mag} \quad M_* = 1.2^{+0.6}_{-0.3} \times 10^{11} M_{\text{sun}}$$

$$M_B = -21.8 \sim L^* \text{ at } z \sim 2$$

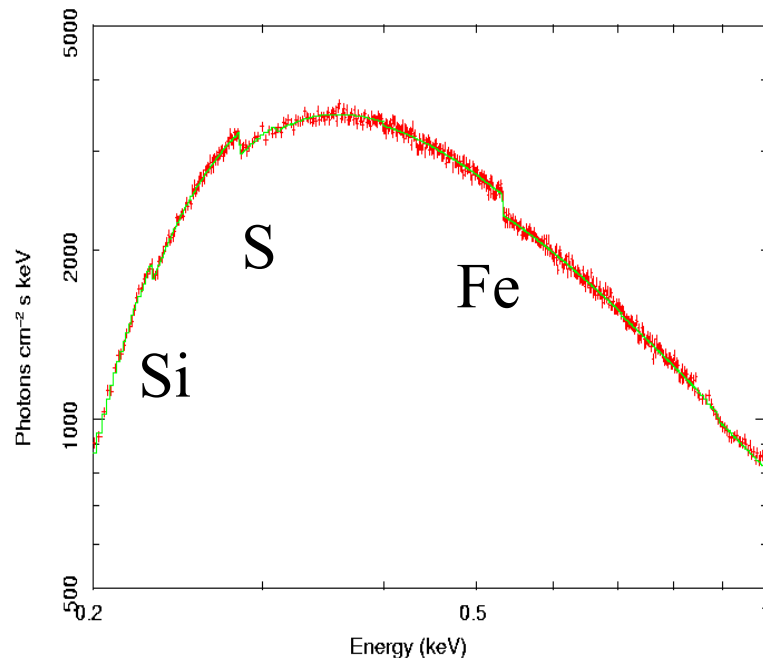


# GRB 080325: A dark GRB in a metal-rich host?



# X-ray vs. optical/NIR

- ◆ **Optical/NIR afterglow detection rate only ~50%**
  - ◆ X-ray afterglow detection ~100%
- ◆ **optical: metallicity measurements affected by dust**
  - ◆ some elements condensed in dusts



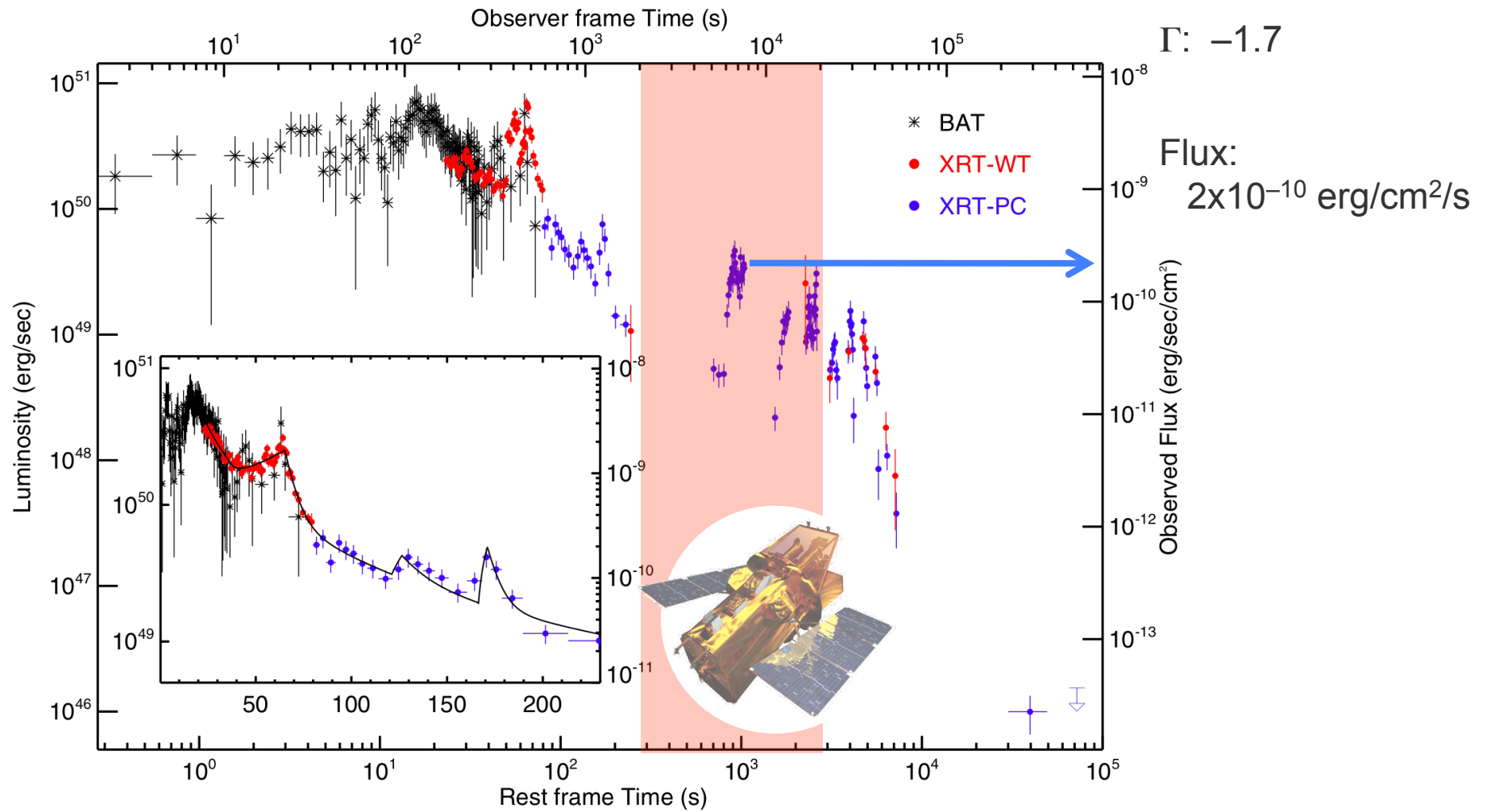
- ◆ **X-ray absorption edge**
  - ◆ redshift
  - ◆ metallicity

X-ray edges by  $N_H = 5 \times 10^{22} \text{ cm}^{-2}$   
with 1/3 solar for GRB at  $z=7$

# Observing Gamma-Ray Bursts with ASTRO-H



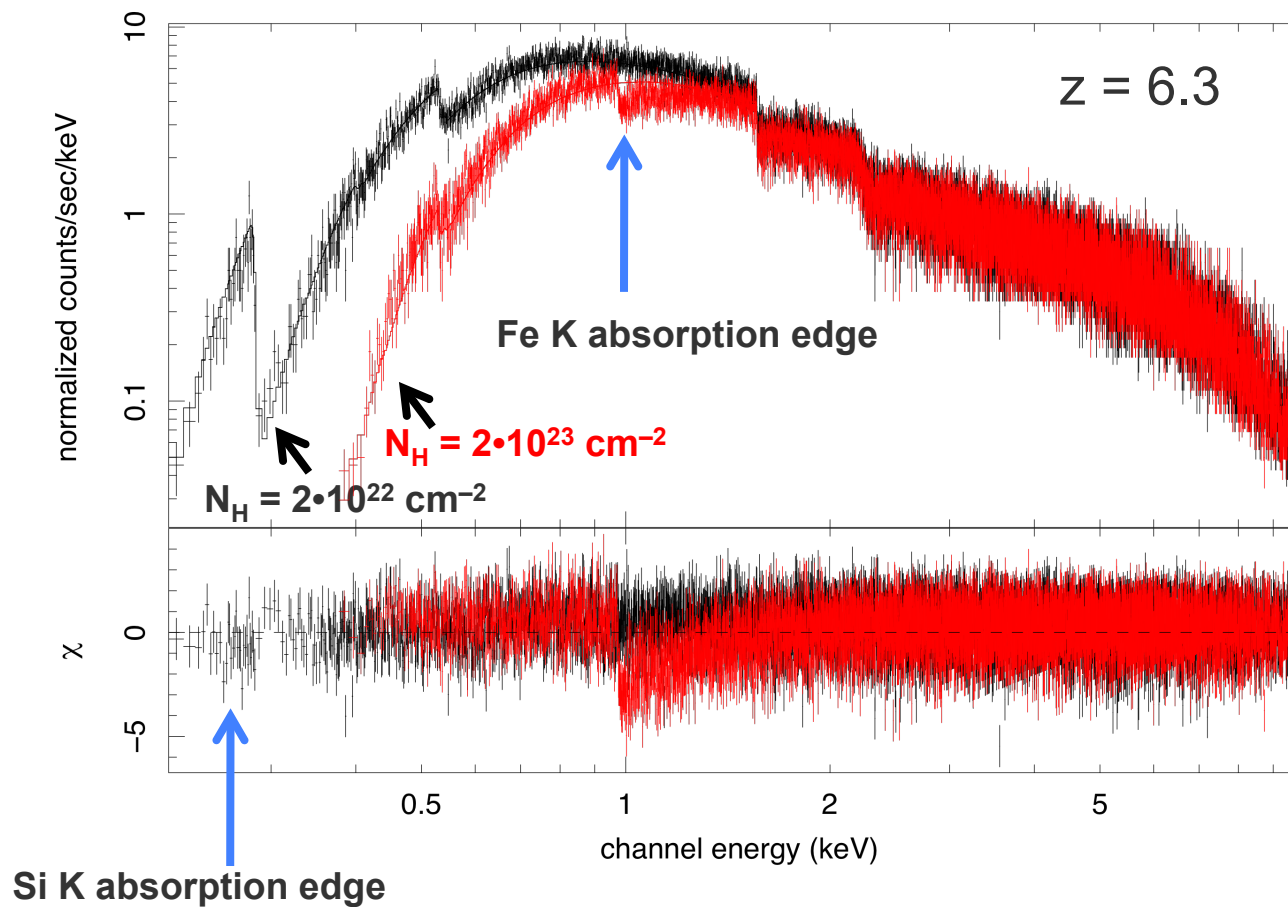
**Simulation: GRB 050904 at  $\sim 10^4$  s after onset**



# Observing Gamma-Ray Bursts with ASTRO-H



**Simulation:** GRB 050904 at  $\sim 10^4$  s after onset



Flux:  $2 \cdot 10^{-10} \text{ erg/cm}^2/\text{s}$

$\Gamma$ :  $-1.7$

$z=6.30$ ,  $Z=1.0$

Exposure: 20 ks

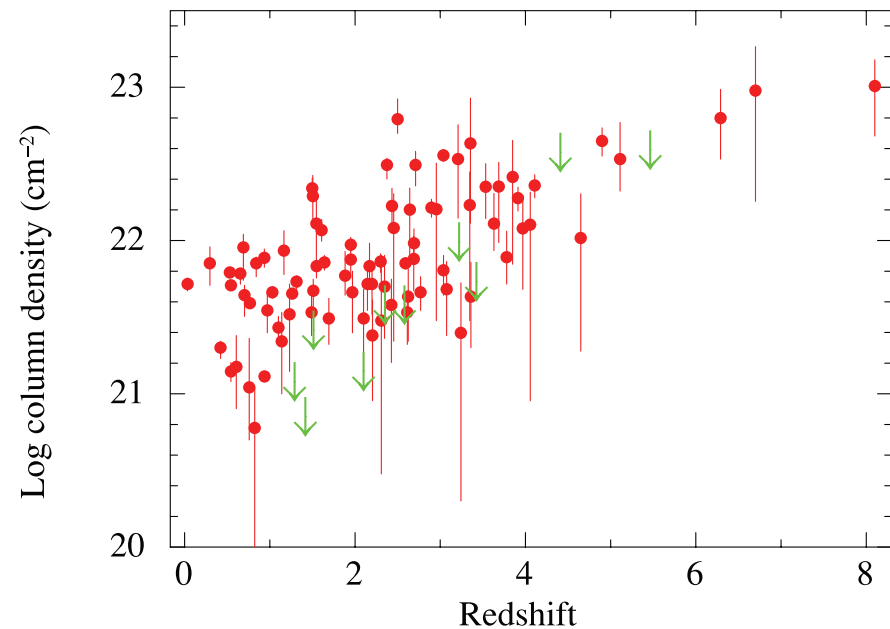
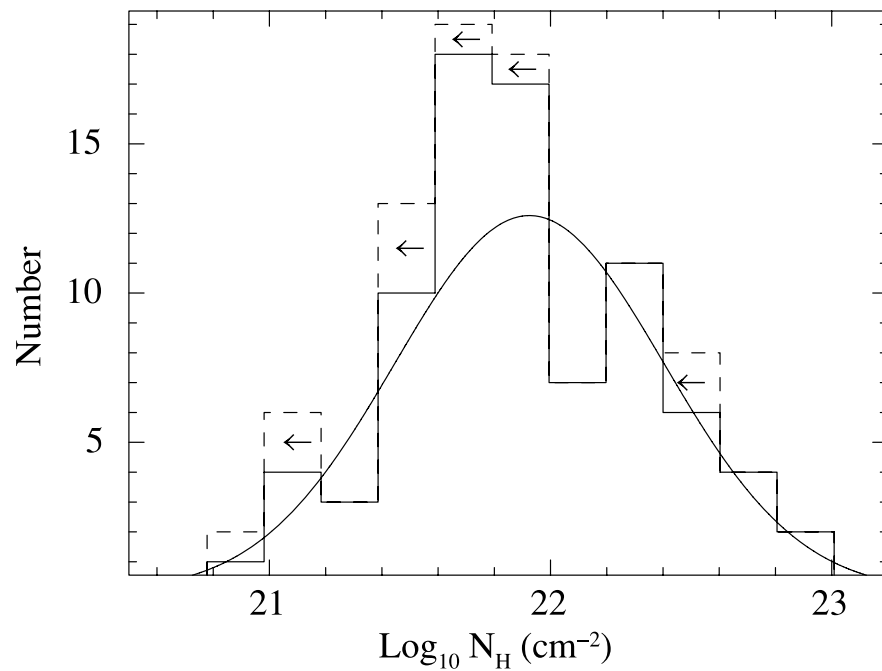
$N_H = 2 \cdot 10^{23} \text{ cm}^{-2}$

$\rightarrow z = 6.29 \pm 0.01$

$Z_{\text{Fe}} = 0.94 \pm 0.06$

# High X-ray absorption column density ( $10^{22} \sim 10^{23} \text{ cm}^{-2}$ ) may be expected at high $z$

93 Swift GRBs with known redshifts, solar abundances assumed



Campana et al. 2010

# Conclusion

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- **GRB is a unique probe for the early Univers**
  - IGM neutral fraction by damping wing!
  - Metallicity through absorption lines/edges
  - Star formation rate by GRB rate vs. redshift
- **currently hampered by small event rate and insufficient sensitivity in NIR spectroscopy!**
  - 30m telescopes / JWST sufficiently sensitive
  - Need more event
  - **optimized GRB mission needed!**
    - EDGE/Xenia, Janus, EXIST
- **ASTRO-H can be a pathfinder for Xenia**
  - can measure metal absorption edges of high- $z$  GRBs